Plasma Plume Characteristics of Cluster Operation of Self-Field Magnetoplasmadynamic Thruster

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Abstract: Magnetoplasmadynamics (MPD) thruster is an appropriate thruster for future space missions that high power operation is required. High power discharge is a risk for spacecraft. Multiple MPD thrusters should be mounted on the spacecraft to ensure redundancy. Moreover, we proposed that the cluster operation of Self-Field MPD thruster that has an advantage from the viewpoints of thermal design, electrode erosion and risk hedge for malfunction. In addition, MPD cluster system could be operated higher power in total than single MPD thruster. However, the interference between each MPD thrusters has not been clarified. Therefore, we conducted the experiment of cluster operation of self-field MPD thruster and the measurement focused on plasma plume.

Nomenclature

d	=	distance from MPD nozzle, mm
D	=	plasma plume diameter, m
F	=	thrust, N
I	=	discharge current, A
$\dot{m}$	=	mass flow rate, g/s

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mi	=	proton mass, 1.67×10^{-27} kg
ne	=	electron density, m^{-3}(≈plasma density)
r	=	plasma plume radius, m
R	=	resistance, Ω
t	=	time after MPD ignition, ms
Te	=	electron temperature, eV
u	=	plasma velocity, m/s

I.Introduction

Magnetoplasmaplasmadynamic thruster (MPD) is an appropriate thruster for future space missions, for example, manned exploration of Mars, short-term space orbit transitions and interplanetary transportation. MPD thruster is high power electric propulsion by electromagnetic acceleration and produce large thrust. Figure 1 shows the principle of thrust generation of MPD thruster. MPD thruster has an advantage of high thrust density compared with other electric propulsion system like ion and Hall thruster using electrostatic acceleration. A high power MPD thruster can achieve both high specific impulse and high thrust weight ratio. High power MPD thruster experiments need several hundred kW or MW power. MPD thruster on the spacecraft is capable of steady operation. Some experiments of MPD thruster was conducted steady state[1]. Some MPD experimental models have thruster head cooling mechanism and could be operated in several tens or one hundred kW. However, many experiment of high power MPD thruster, up to several hundred kW or MW, was conducted quasi-steady state[2-5] or pulse because of the problem of power supply and thermal lord of the experimental facilities. In addition, it is also necessary to consider the thermal design of MPD thruster heads because it is electrode for arc discharge. Many experimental and numerical research[6,7] are conducted to optimize MPD thruster for future space missions.

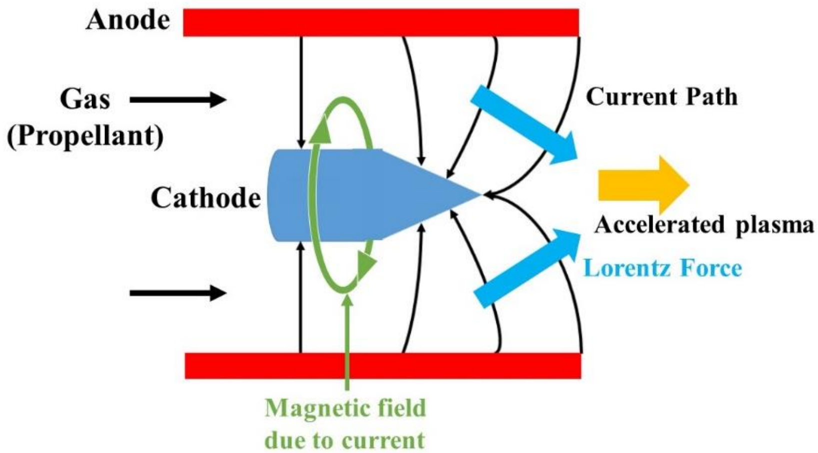

Figure 1. Thrust principle of Magnetoplasmadynamic Thruster

II.Objectives

We proposed that the cluster operation of self-fields MPD thruster. And we conducted the cluster operation of self-field MPD thruster. Clustered MPD thruster system has advantage from the viewpoints of thermal design, electrode erosion and risk hedge, and the system contributes to the increase power. In this case, interference during operation between each MPD thrusters become problematic. Especially, the crosstalk between the plasma plumes of each MPD thrusters has been observed, it is inferred that the propulsive characteristics are affected. In this paper, we assessed the plume characteristics of MPD cluster.

III.Experimental Setup

A. Self-Field Magnetoplasmadynamic Thruster

The MPD thruster we used is self-field MPD thruster. A self-field MPD thruster has simple structure, it does not have magnetic fields generator outside nozzles. We can design MPD thrusters cylindrical shape compactly. Our MPD thruster used hydrogen as propellant. The flow rate of propellant can be controlled by adjusting the pressure of reserve tank which put in the vacuum chamber. The mass flow rate of the gas is adjusted $\dot{m}$ = 1.0 to 1.8 g/s. The electrode of each MPD thruster have segmented-anode, the MPD thruster has eight azimuthally-located Mo anode rods with a diameter of 8mm and one 2% Th-W cathode rod with a diameter of 16 mm. The inside diameter of thruster nozzle is 50 mm. The nozzle inner wall is electrical insulation made by boron nitride. Figure 2 shows the schematic and the photograph of self-field and anode-segmented MPD thruster.

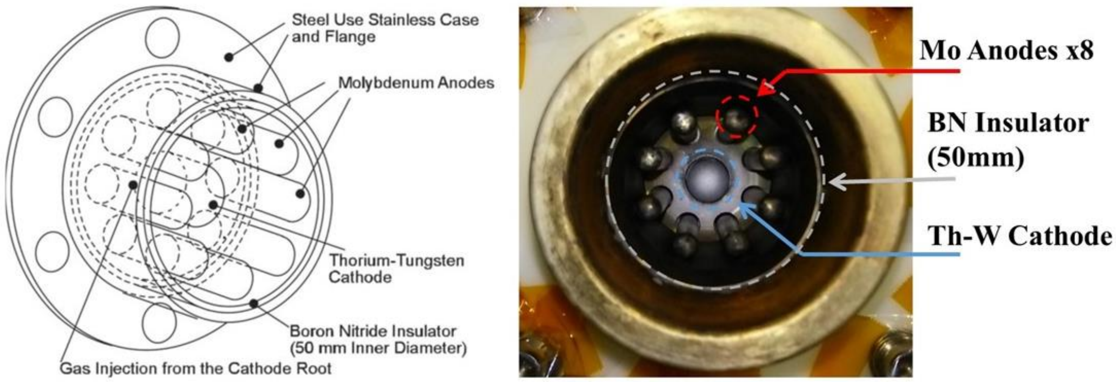

Figure 2. Schematic (left) and Photograph (right) of Self-field and Anode-Segmented type Magnetoplasmadynamics (MPD) thruster

B. MPD cluster system

Figure 3 shows the schematic of the experimental configuration of MPD cluster. We used three MPD thrusters of the same design. Three MPD thruster were mounted aluminum turret in vacuum chamber and consisted MPD cluster. Those MPD thrusters are mount on each one located at equal intervals on the circumference 350 mm in diameter. We operated three MPD thrusters at the same time. Figure 4 shows the photograph of MPD cluster installed chamber wall. The MPD cluster system requires high input power and it is supplied from the capacitor bank of pulse forming network circuit. Figure 5 shows the circuit of Pulse forming network. The power supply system operates about 1 ms quasi-steady discharge, and the power circuit can supply about 18 kA current in total at maximum. The critical current of MPD thruster is estimated about 12 kA. If the current of MPD thruster exceeds the critical current, the discharge of MPD thruster is unstable. However, the operation current per one unit is about 6 kA, it is lower than the critical current. Whether arc discharge of MPD thruster is stable or not depends not only on the discharge current but also on the flow rate of propellant gas. The small tanks and fast valves for gas was installed in chamber. Generally, in the case of low flow rate or low discharge current operation, MPD thruster is often unstable. Anode-segmented MPD thruster is easy to be stable for the operation of those conditions, because the current path of MPD thruster is fixed. For that reason, despite the complex operation of multiple units operating simultaneously, this MPD cluster system operated stably in many conditions, particularly in the low gas flow rate condition.

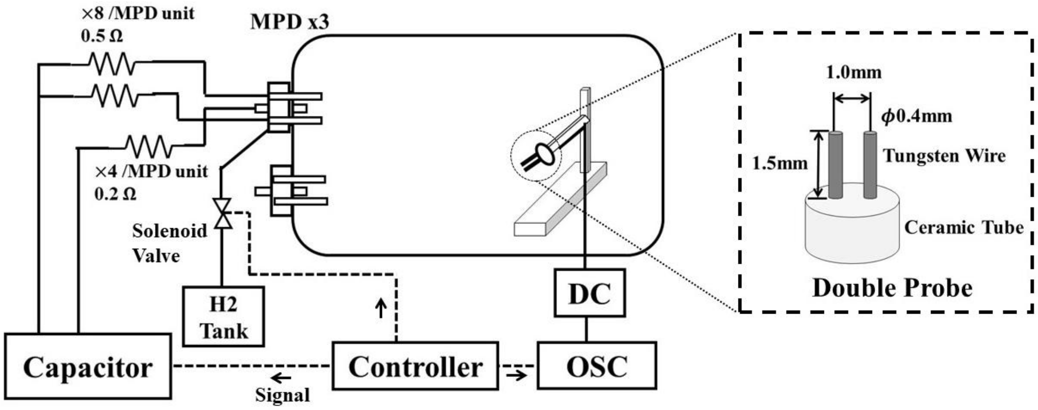

Figure 3. Schematic of experimental configuration of MPD cluster

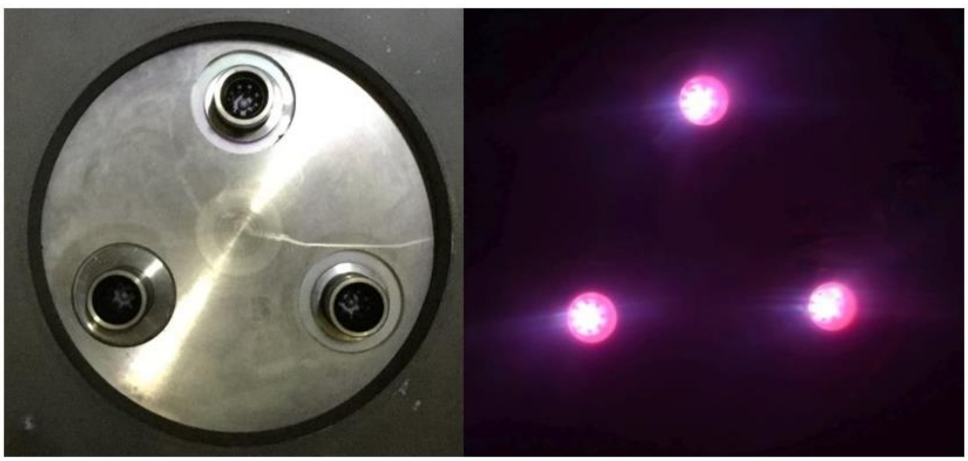

Figure 4. Photograph of MPD cluster system on the wall of the chamber (left: out of operation, right: MPD cluster in operation)

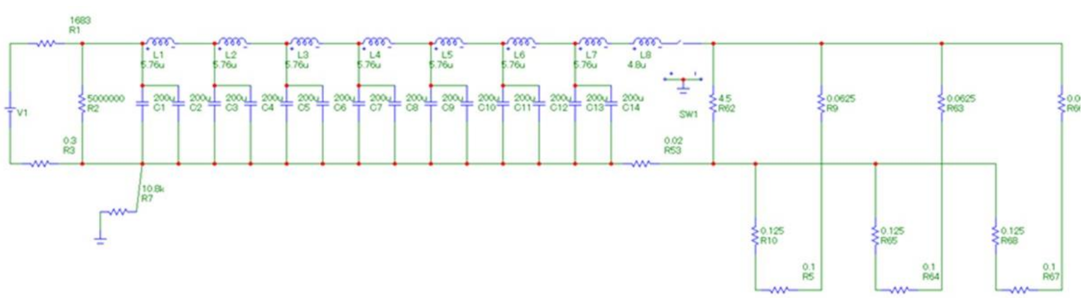

Figure 5. Circuit of Pulse Forming Network

C. Vacuum systems

The experiment of MPD cluster was conducted in the vacuum chamber in ISAS/JAXA. The chamber size is 2 m in diameter by 3 m length. The vacuum chamber has a rotary pump, mechanical booster pump and molecular pump. The back pressure of the chamber at this experiment is under 3.0×10^{-3} Pa. The power and gas are introduced from outside. The probes were installed inside chamber. DC power supplies and resistors for probe are installed outside of the chamber.

D. Measurement Instrument

We conducted plasma plume measurement using double probe. The double probe head is two tungsten wires and ceramics tube. The distance of two wires about 1 mm, it is smaller than the Debye length in this experiment, several tens of micrometers. The tungsten wire could collect the ion current from the plasma. The probe connected with power supply and R = 5.1 Ω resistor. We measured the voltage of power supply and the resistor. We calculated the current through the resistor, and plot the current-voltage characteristics. We can understand the plasma parameter, plasma density and plasm temperature from the characteristics.

IV.Result

Figure 6 and Figure 7 shows the plasma number density and electron temperature of MPD cluster plasma plume measured using double probe at 1250 mm from MPD nozzle surface. The measurement was conducted along the radial direction.

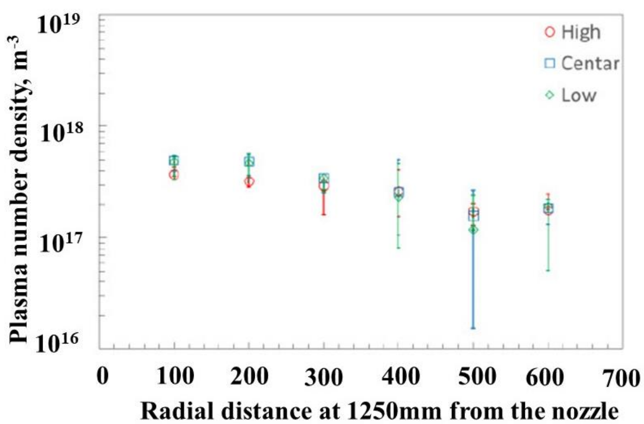

Figure 6. Plasma density of MPD cluster

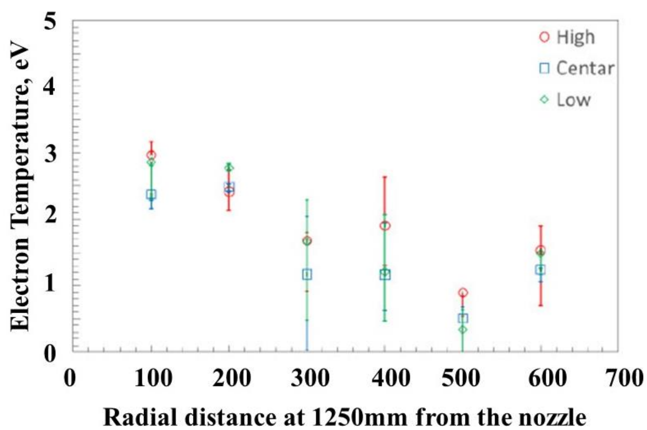

Figure 7. Electron temperature of MPD cluster

Following Figure 4, the plasma density is n = 3.3×10^{17}m^{-3} or more in the radial range of r = 600 mm from the plume center. Therefore, we confirmed a uniform plasma region with a diameter of D = 1200 mm at the distance of d = 1250 mm from the MPD nozzle.

We conducted the velocity measurement by Time-Of-Flight method. Figure. 6 shows the ion saturation current of plasma plume using double probe, it is biased 10 V. We measured the ion saturation current at two point. The front probe is d = 1240 mm, and the rear probe is d = 1260 mm. The distance between two probes is 20 mm. The waveform of this probe output has the region where it can be considered a flat top 0.4 ms between 0.8 ms after the ignition. We extracted and replot the waveforms from t = 0.6 to 0.7 ms. The time interval is just 1 ms in the center of the flat top region. Figure 7 shows the waveform on the same time of front and back probe. The output signal of the rear probe is delayed from the signal of the front probe. The delay is about 7.2×10^{-7} s. Therefore, we could determine the plasma velocity is 28 km/s by Time-Of-Flight method.

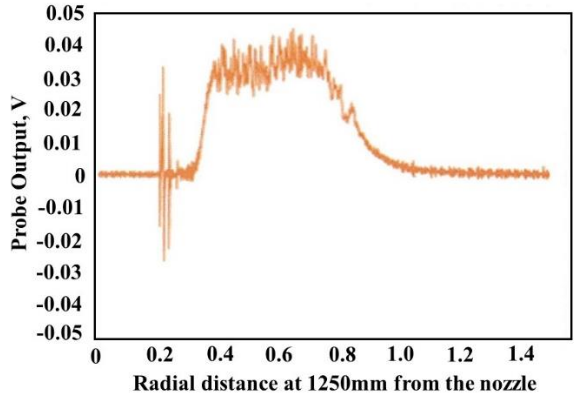

Figure 8. Ion saturation current of MPD thruster

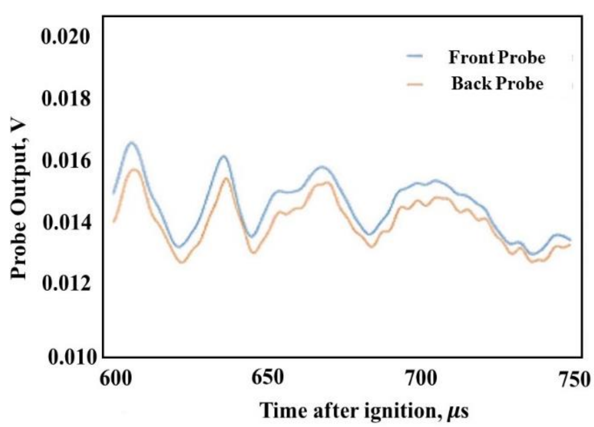

Figure 9. Waveforms of ion saturation current of MPD thruster (Time-Of-Flight method)

We constructed MPD cluster system and conducted the experiment to assume the plasma plume by generated three MPD thrusters. We observed that mixed plasma plume that MPD cluster produced. We conducted plasma measurement using double probe to determine the plasma density and the electron temperature. We assessed the plasma velocity by Time-Of-Flight method. Moreover, we identified the plasma plume of MPD cluster become larger than single MPD.

V.Discussion

In our previous study about single operation of our MPD thruster, we confirmed a uniform plasma region with a diameter of D = 600 mm at the distance of d = 750 mm from the MPD nozzle and with a diameter of D = 1200 mm at the distance of d = 1250 mm from the MPD nozzle and The plasma and plasma velocity measured u = 25 km/s. Figure 10 summarizes the plasma plume size and plasma parameter of the single and cluster operation of MPD thrusters. Considering the accuracy of TOF method, single operation and cluster operation have almost same velocity. The thrust of MPD thruster is the following equation.

$$F = m_i n v^2 \frac{\pi D^2}{4} \quad (1)$$

If we operated single MPD in I = 11.6 kA a, it is close to theoretical critical current[9], $n = 3.3.\times 10^{18}$ m^{-3}, u = 47 km/s, D = 0.6 m, at d = 1250 m from MPD nozzle, and F = 3.44 N. In this case, the discharge voltage of MPD, measured between anode and cathode, was 170 V and input power of MPD nozzle was 2.0 MW. If we operated MPD cluster in I = 16.7 kA, $n = 3.3 \times 10^{17}$ m^{-3}, u = 28 km/s, D = 1.2 m, , at d = 1250 m from MPD nozzle,, and F = 0.48 N. (Fig. 10) In this case, the discharge voltage was 110V and input power of MPD nozzle was 1.8 MW. MPD cluster system used many resistors to divide input power evenly. Those resistors and long electrical lines made voltage drop and power losses.

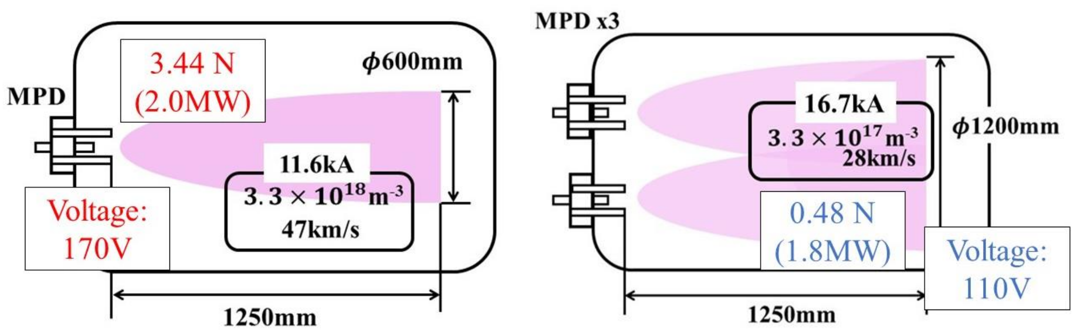

Figure 10. Plasma plume of single and cluster operation of MPD thruster

VI.Conclusion

From the above, the thrust produced by the MPD thruster system depends on the input power to a unit of MPD rather than the total input power. This fact shows that the installation of only one larger size and higher power MPD thruster produces larger thrust than the installation of multiple MPD thrusters. And we succeed the operation of MW class MPD cluster system. The single operation of MPD in I = 11.6 kA produced the largest thrust in our experiments. In this condition, the discharge current of MPD unit is almost same the critical current of MPD. The thrust of MPD is limited by the critical current. Therefore, we could not apply power to this MPD thruster. In other words, if we obtain larger thrust using this MPD, we can only use MPD cluster. If we can operate all MPD thrusters at the critical current, the thrust of MPD thruster system is maximized. If we update the power supply systems, the cluster operation will produce larger thrust than the single operation. For that reason, we concluded MPD cluster operated several tens MW class or more power is suitable for super power spacecraft, using super large solar panel or fusion reactor, for future deep space mission including interstellar flight.

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