Experimental Investigation of Thrust Characteristics of Magnetoplasma Sail

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Abstract: Magnetoplasma Sail (MPS) is one of the next generation in-space propulsion systems that utilize the interaction between the solar wind and the magnetosphere by way of an artificial magnetic field. The thrust characteristics of MPS with plasma injection has been experimentally investigated as a function of the magnetic moment M, the dynamic pressure of the injected plasma P_{inf} and the dynamic pressure of the simulated solar wind P_{sw}. The thrust measurements were used a pendulum type thrust stand. The thrust gain is growing both with β_k value which is ratio of the dynamic pressure of the injection plasma to the magnetic pressure, but the thrust saturation was observed at the high β_k condition at the injection point (β_k~1). The maximum thrust gain in this paper which is the ratio between the thrust with plasma injection and the thrust without plasma injection was about 4.1.

Nomenclature

Δt	=	operation time (0.8 ms)
C_d	=	thrust coefficient
F	=	Thrust, N
L	=	Magnetospheric size, m
M	=	Magnetic moment, Tm^3
P	=	Dynamic pressure, Pa
r_c	=	radius of coil, m
Rm	=	Magnetic Reynolds number
S	=	blocking area of magnetosphere, m^2
u	=	Velocity, m/s
β_k	=	β_k value ($P/B^2/2\mu_0$)
δ	=	Skin depth, m
μ_0	=	magnetic permeability, H/m
ρ	=	density, kg/m^3
0	=	injection point index

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sw = Solar wind index
inf = injection plasma for inflation index
Mag = Magsail index
MPS = Magnetoplasma Sail (MPS) index

I. Introduction

SEVERAL types of In-Space propulsion systems have been studied for their use in sufficiently reducing costs and travel time. Magnetoplasma Sail (MPS) is one of the next generation in-space propulsion systems that utilize the interaction between the solar wind and the magnetosphere by way of an artificial magnetic field[1,2]. MPS provides a large blocking area to the solar wind particles by creating artificial magnetic field to deflect the charged solar wind particles that converts the solar wind momentum into the momentum of the spacecraft (Fig.1). This blocking area is called a magnetosphere. The magnetosphere is created by a superconducting coil on the spacecraft. The thrust of MPS is formulated as

$$F = C_d \frac{1}{2} \rho_{sw} u_{sw}^2 S \quad (1)$$

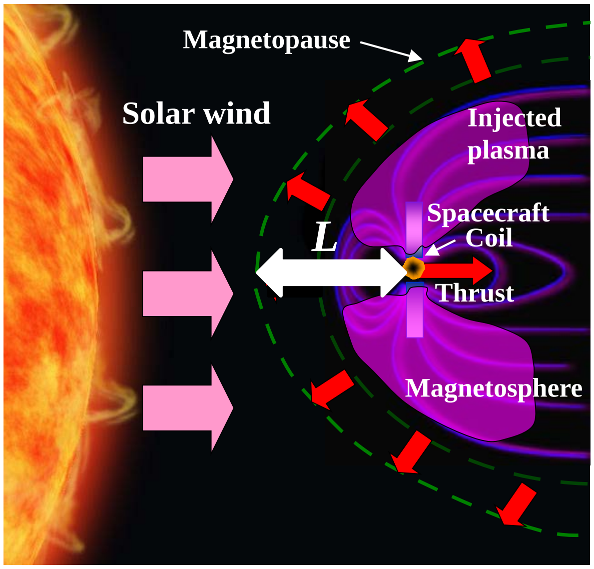


Figure 1. Magnetoplasma Sail (MPS).

where F is the thrust of MPS, C_d is the thrust coefficient, $1/2\rho_{sw}u_{sw}^2$ is the dynamic pressure of the solar wind and S is the blocking area. We assume that the blocking area of the magnetosphere, S, is estimated as $S=\pi L^2$. We define the magnetospheric size, L, as the distance from the coil center to the magnetopause (Fig.1). The thrust of MPS strongly depends on the magnetospheric size, and the magnetospheric size is in turn proportional to the magnetic moment, M ($L=M^{1/6}$), where $M=\mu_0 nJr_c$ and r_c is the radius of the coil. Therefore to increase the thrust, either a large coil or a high current coil is required. Generally, the coil size is limited by the rocket size, and consideration of implementing a superconducting coil (φ3.5 m in diameter, 5000 turns, 200 A) for use in MPS has been discussed[3]. In this present work, the magnetospheric size L is about 300 m, and the thrust from the MPS is 3 μN (as estimated by Eq.(1)), an insufficient amount for deep space exploration. Alternatively, the thrust could be increased by expanding the magnetosphere by plasma injection, an idea first proposed by Winglee[2], called magnetosphere inflation. In MPS study, we aim to increase the magnetospheric size by several kilometers as well as increase the thrust class to 100 mN by magnetosphere inflation. Several investigations have been conducted on the mechanism of MPS and on the estimation of thrust characteristic using numerical simulations and scale model experiment. The thrust transfer process was clarified by magnetohydrodynamic (MHD) simulation, and the characteristic survey of the magnetosphere inflation and the thrust characteristics were conducted by previous numerical simulations[4-7]. The magnetosphere inflation experiment was previously conducted, and the thrust characteristics of MPS without plasma injection were clarified in laboratory experiment[8-9]. The current important problem of MPS is the clarification of the thrust gain characteristics by the magnetosphere inflation. This discussion has performed by the numerical simulation[10,11]. It was reported that the thrust gain by plasma injection is depended on β_k value at the injection point. The numerical simulations do not include all physical phenomena and/or the wide scale simulation. It is important to both clarify the thrust characteristics and to verify all of the physical phenomena and principles of MPS by way of laboratory experiment. The thrust gain was experimentally measured by author in the previous study, but this result is insufficient for clarification of the thrust gain characteristics, which the previous experiment investigated dependence of the magnetic moment and β_k value on thrust gain of MPS[12]. In this study, the thrust characteristics of MPS with plasma injection has been experimentally investigated as a function of the magnetic moment M, the dynamic pressure of the injected plasma P_{inf} and the dynamic pressure of the simulated solar wind P_{sw}.

II. Scaling parameter

The laboratory experiment was designed such that the plasma flow follows the similarity law of MPS in space. We use the following scaling parameters of the magnetosphere (listed in Table 1): the ion Mach number, the ratio between the ion Larmor radius and the magnetospheric size r_{Li}/L, the ratio between skin depths and the magnetospheric size δ/L, and Magnetic Reynolds number R_m. These parameters in Table.1 are obtained for typical solar wind plasma (u_{sw} =400 km/s, n_{sw}=5×10^6 m^{-3} and T_i~10 eV). Each scaling parameter of MPS is required as follows:

$$\delta / L << 1 \quad (2)$$

$$\mathrm{R_m} >> 1 \quad (3)$$

$$\textit{Ion Mach number} > 1 \quad (4)$$

The required performance of the simulated solar wind is that n_e>3x10^{17} m^{-3} and u_{sw}>20 km/s[13]. In the MPS ground simulation, r_{Li}/L can be achieved within a range, 0.1<r_{Li}/L<2, simulated for the magnetospheric size class of 10-100 km and thrust class of 10-100 N. In the laboratory, the collision effect is inevitable such that *Rm*~10 is small compared to that observed in space, *Rm*~10^8. The hybrid PIC simulation conducted by Kajimura[14] included an ion-neutral collision, and it was reported that the thrust of MPS in the laboratory is undervalued compared to that of collisionless plasmas in space.

The scaling law of the magnetosphere inflation and thrust gain are shown as follows, from the simple one-dimension model:

$$\frac{L_{MPS}}{L_{Mag}} = \left(2^{6/n-2} \left(\beta_{k0}^{1/2} \frac{P_0}{P_{sw}} \right)^{3/n-1} \right)^{1/6} \quad (5)$$

$$\frac{F_{MPS}}{F_{Mag}} = \frac{C_{d\_MPS}}{C_{d\_Mag}} \left(\frac{L_{MPS}}{L_{Mag}} \right)^2 \quad (6)$$

where L_{MPS} is the magnetospheric size with the plasma injection, L_{Mag} is the magnetospheric size without the plasma injection, *n* is the multiplier factor of the magnetic field distribution, β_{k0} is β_k value at the injection point and β_k value is ratio of the dynamic pressure of the injection plasma to the magnetic pressure. P_0 is the dynamic pressure of the injection plasma at the injection point and P_{sw} is the dynamic pressure of the solar wind. The development of Eq.(5) is shown in appendix. Equation (6) is the thrust gain by the Eq.(1) and Eq.(5). F_{MPS} is the thrust with the plasma injection, F_{Mag} is the thrust without the plasma injection. The thrust gain depends on $\beta_{k0}^{1/2}P_0/P_{sw}$, according to Eq.(5) and Eq.(6). Given by the scaling law of the magnetosphere, a high dynamic pressure is required to simulate the solar wind in the laboratory (P_{sw} ~0.1-10 Pa, whereas in space, P_{sw}=10^{-9} Pa). Therefore, $\beta_{k0}^{1/2}P_0/P_{sw}$ is about 10^{-1}-10^2 in this experiment (P_{sw}=0.1-10 Pa, β_{k0}=0.001-1, P_{inf}=10-100 Pa), whereas in space, $\beta_{k0}^{1/2}P_0/P_{sw}$ is about 10^7-10^9 (P_{sw}=10^{-9} Pa, β_{k0}=0.001-1, P_{inf}=10-100 Pa). It is predicted that the magnetosphere inflation rate is only 1-2 in the laboratory. In this work, we show by way of a laboratory experiment that the magnetosphere inflation and the thrust increase by plasma injection. We investigate the thrust characteristic within a realizable experimental condition in the laboratory, and use this result to predict the thrust on a space scale.

Table 1 Typical and scaling parameter of MPS.

Parameter	Magnetoplasma Sail	
	Space	Laboratory
Operation time, Δt	-	0.8 ms
Magnetospheric size, *L*	10-100 km	~0.1 m
Thrust, *F*	10-100 N	0.1-1 N
Scaling parameter		
Ion Mach number	~8	<1
Ratio between Larmor radius and Magnetospheric size (r_{Li}/L)	~1	~1
Ratio between skin depth and Magnetospheric size (δ/L)	<1	<1
Magnetic Reynolds number (*Rm*)	~10^8	~10
Scaling parameter of magnetopshere inflation ($\beta_{k0}^{1/2}P_0/P_{sw}$)	10^7-10^9	10^{-1}-10^3
Magnetospheric size increasing rate (L_{mag}/L_{mps})	6-10	1-2

III. Experimental Setup and Conditions

A. Experimental Facility

The experimental setup for this study consists of a vacuum chamber (diameter: 2 m; length: 3 m), a solar wind simulator (SWS), a Magnetoplasma Sail Simulator (MPSS), a Pulse Forming Network (PFN), a gas supply system, and the measuring system (Fig. 2). A large test section (>φ1000 mm in diameter), high density (>3×10^{17} m^{-3}) and high velocity (>20 km/s) are required for the solar wind simulator. We employ the triple quasi-steady MPD arcjet as the solar wind simulator[15]. The triple MPD arcjet is mounted on a flange of the vacuum chamber, each one located at equal intervals on the circumference 350 mm in diameter. The discharge chamber of the MPD arcjet has an inner diameter of 50 mm and a length of 100 mm. The arcjet itself consists of eight azimuthally-located molybdenum anode rods (diameter: 8 mm; length: 70 mm) and a short thoriated tungsten cathode rod (diameter: 20 mm) surrounded by an annular floating body and insulators. The electrodes are operable over a range from low current discharge to erosive high current discharge. The MPSS consists of the solenoid coil (the 76-mm-diameter and 20-turn) and two Mini-MPD arcjets for the magnetosphere inflation. The schematic of the MPSS is shown in Fig.3. Two Mini-MPD arcjets are positioned inside the solenoid coil and the plasma jet flows in the vertical direction of the coil. The MPSS is located at the 1250 mm from the SWS, and is fixed on the thrust stand. The Mini-MPD arcjet consists of copper anode (24 mm in diameter), a thoriated tungsten cathode rod 11 mm in diameter, both pieces surrounded by insulators. Two Mini-MPD arcjets can operate equally and simultaneously by splitting resistance between them. The simulator operation requires high input electricity, supplied from the PFN that operates in a 1 ms, quasi-steady mode. A high-speed mini solenoid valve allowed us to feed gaseous propellants in a rectangular waveform into the SWS and the Mini-MPD arcjet. The valve opens and closes to allow the gas in the reservoir to flow through choked orifices 3 mm in diameter. The mass flow rate of the hydrogen gas was controlled by adjusting the reservoir pressures, thus obtaining a gas pulse of about 5 ms, and a flow rate of 0.1 g/s.

Typical snapshot of the MPS thrust measurement is shown in Fig.4. The simulated solar wind comes from left side. The triple MPD arcjet produced flat plasma jets more than *φ*1200 mm[15]. The MPSS was fixed on the thrust stand (Fig. 4). The plasma jet for the magnetosphere inflation was situated equally by the upper and lower sides of the coil.

B. Experimental Condition

Operation conditions and typical values for the MPS thrust measurements are listed in Table 2. β_{k0_inf} is the ratio between the plasma dynamic pressure and the magnetic pressure at the injection point, and r_{Li_inf}/L is the ratio

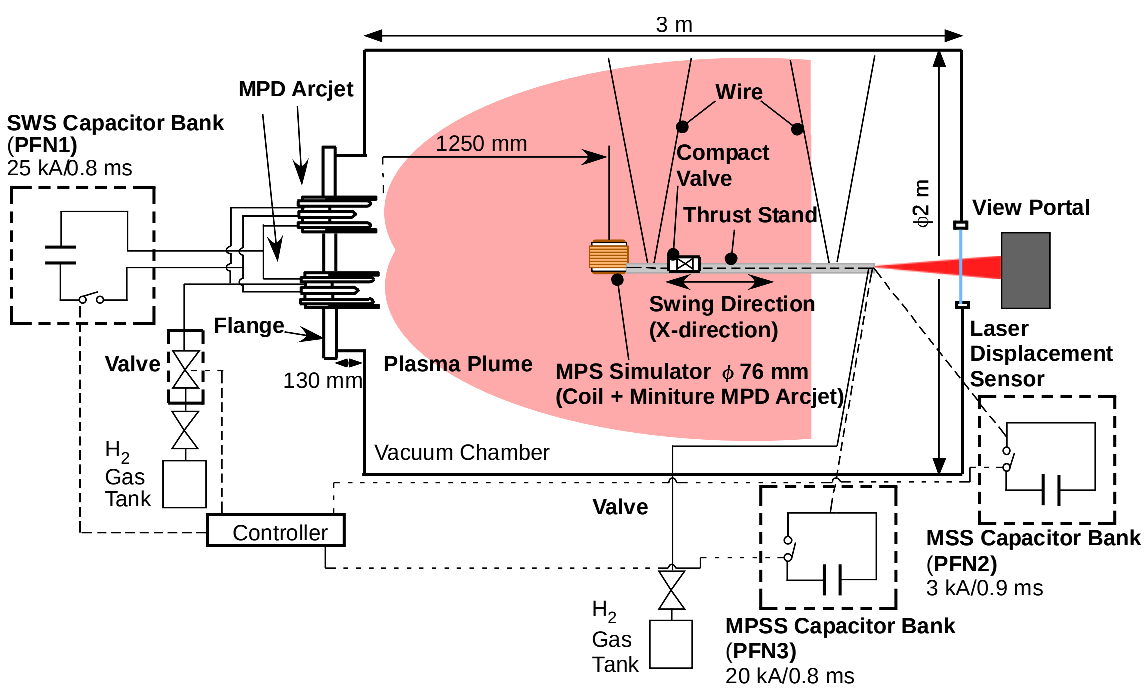


Figure 2. Schematics of MPS experimental facility.

between the ion Larmor radius at the plasma injection point and the magnetospheric size. The plasma parameters of the simulated solar wind are obtained by taking measurements at a distance of 1250 mm from the discharge chamber. The conditions of the SWS is 2 conditions (P_{sw}=0.34 Pa and P_{sw}=2.9 Pa). The plasma parameter of the Mini-MPD arcjet for the magnetosphere inflation (measuring position is 70 mm from the outlet of the Mini-MPD arcjet) is P_{inf}=19-81 Pa. The thrust measurement experiment is conducted for 7 conditions of the discharge current of the coil. All non-dimensional parameters presented here were estimated by extrapolating the results between 70 mm to 200 mm from the outlet of the Mini-MPD arcjet.More than twice the magnetosphere inflation was measured by the previous magnetosphere inflation experiment, P_{sw}=2.9 Pa, P_{inf}=81 Pa, M=2.2×10^{-5} Tm^{3}. Figure. 5 show the snapshot of the typical previous magnetosphere inflation experiment. We can see the magnetosphere around the coil by the interaction between the solar wind and magnetic field, and we can find a dark region which may correspond to magnetopause. The magnetopause is expanded in the radial direction of the solar wind.

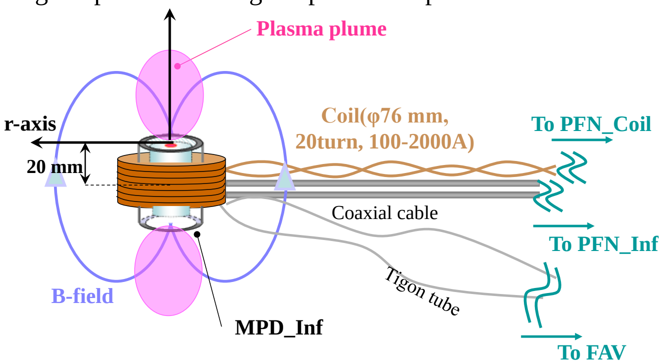


Figure. 3 Magnetoplasma sail simulator.

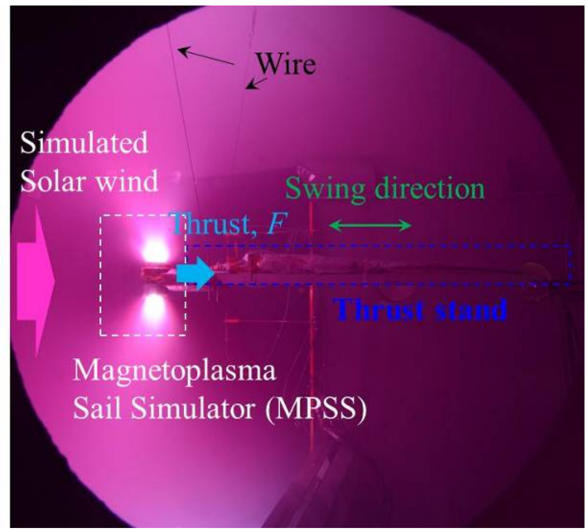
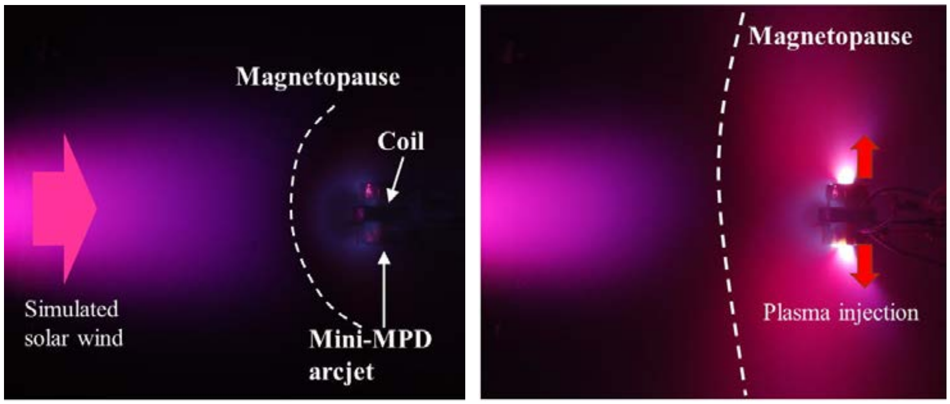


Figure 4. Typical snapshot of MPS experiment. (Coil:0.61 kA, 2.2×10^{-5} Tm^{3}, Shatter Open).

Table 1. Operating conditions and plasma parameters of solar wind simulator, coil and Mini-MPD arcjet simulating MPS spacecraft.

Simulated Solar Wind		
Number Density, m^{-3}	3.0×10^{17}	1.2×10^{18}
Electron Temperature, eV	3.5	5.1
Velocity, km/s	26	38
Dynamic pressure, Pa	0.34	2.9
Plasma Source for Magnetosphere Inflation		
Number Density, m^{-3}	1.9-5.4×10^{19}	
Electron Temperature, eV	1.6-1.9	
Velocity, km/s	24-30	
Dynamic pressure, Pa	18-81	
Solenoid Coil		
Discharge Current, kA	0.11-1.9	
Magnetic Moment, Tm^{3}	1.3-22×10^{-5}	
Magnetic Field at coil Center, T	0.04-0.62	
Non-Dimensional Parameter		
β_{k0}	0.0026-0.79	
r_{Li_inf}/L	0.0013-0.065	
$\beta_{k0}^{1/2}P_0/P_{sw}$	8-1140	



(a) without plasma injection **(b) with plasma injection**

Figure 5. Snapshot of the previous magnetosphere inflation experiment (P_{sw}=2.9 Pa, P_{inf}=81 Pa, M=2.2×10^{-5} Tm^3).

C. Thrust measurement method

The pendulum type thrust stand was employed for thrust measurement of MPS (Fig.2 and Fig.4). The thrust stand consists of a concave aluminum bar, a terminal block to connect the coil and the Mini-MPD arcjet and the target aluminum board to reflect the laser. The stand is 1 m long and is suspended by 4 stainless wires. The stand swings in the direction of thrust generation, and its displacement is measured by a laser displacement censor (KEYENCE LK-G500). The thrust of MPS is generated by blocking the solar wind thus it is necessary to make the blocking area of the thrust stand as small as possible. The displacement waveforms of the thrust stand in SWS+Coil+Mini-MPD mode and SWS+Mini-MPD mode were plotted versus time and fitted by using the least-squares method (see Fig. 6). Ideally, the displacement waveform by the thrust is sine curve. However, the displacement waveforms in Fig. 6 are disturbed waveform, because the force other than the thrust is generated by the non-uniform discharge of two Mini-MPD arcjet. Therefore, in order to include the effect of the yaw and rolling, we use bifilar suspension pendulum model as a model function of least squares method (Fig. 6). The discharge occurred at 0 sec and the cycle length of the pendulum is about 1.5 sec, adequately longer than the MPS discharge time of 1 ms. The thrust stand is swung by the impulse at the operation of the MPS, and the pendulum and displacement sensor combined were calibrated with impulses of known magnitude that were applied to the coil. The largest displacement of SWS+Coil+Mini-MPD mode was about 0.08 mm from an impulse of 0.001 Ns. The impulse of the SWS+Coil+Mini-MPD mode consists of the following components;

・The impulse by the thrust of MPS
・The impulse by the thrust stand blocking neutral gas
・The impulse by the thrust stand blocking plasma flow
・The impulse by the discharge noise of the coil
・The impulse by the discharge noise of the Mini-MPD arcjet

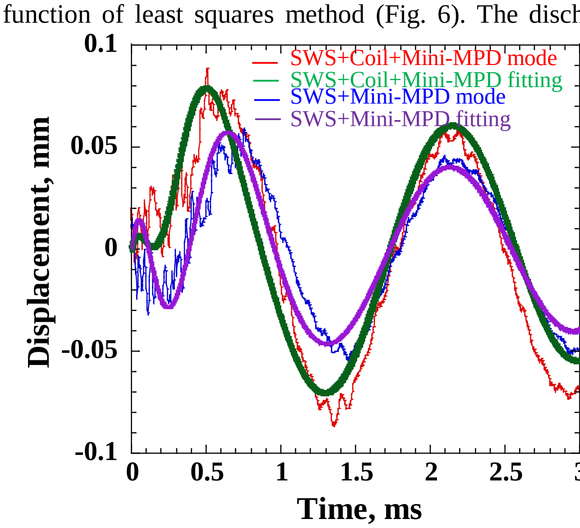


Figure 6. Displacement waveforms of thrust stand and fitted curve. (P_{sw}=0.34 Pa, I_{coil}=0.61 kA, P_{inf}=81 Pa)

In this study, the thrust of MPS was estimated as follows:

$$(F\Delta t)_{MPS} = (F\Delta t)_{total} - (F\Delta t)_{SW+\inf} - (F\Delta t)_{Coil} \quad (7)$$

where $(F\Delta t)_{\mathrm{MPS}}$ is the impulse by the thrust of MPS and $(F\Delta t)_{\mathrm{total}}$ is the impulse of SWS+Coil+Mini-MPD mode containing all of the components discussed above. $(F\Delta t)_{\mathrm{SW+inf}}$ is the impulse of SWS+Mini-MPD mode, and it contains both the impulse by blocking the neutral gas and plasma flow and the impulse by the discharge of the Mini-MPD arcjet. $(F\Delta t)_{\mathrm{Coil}}$ is the impulse of Coil mode, and it is corresponds to the impulse of the discharge noise of the coil. $(F\Delta t)_{\mathrm{Coil}}$ in condition of Fig.6 is very small. From this condition, the difference between the impulse of

SWS+Coil+Mini-MPD arcjet mode and the impulse of SWS+Mini-MPD arcjet is approximately the impulse by the thrust of MPS. In this study, the thrust of MPS without plasma injection was estimated as follows:

$$(F\Delta t)_{Mag} = (F\Delta t)_{SW+Coil} - (F\Delta t)_{SW} - (F\Delta t)_{Coil} \qquad (8)$$

where $(F\Delta t)_{\mathrm{Mag}}$ is the impulse of MPS without the plasma injection, $(F\Delta t)_{\mathrm{SW+Coil}}$ is the impulse of SWS+Coil and $(F\Delta t)_{\mathrm{SW}}$ is the impulse of SWS mode. The thrust of MPS with and without plasma injection is obtained by the operation time as follows

$$F = \frac{(F\Delta t)_{MPS}}{\Delta t} \qquad (9)$$

The operation time of each simulator, Δt, is defined as 0.8 ms (steady state).

IV. Experimental result

The measured thrust is plotted against magnetic moment in Fig.7. It was confirmed that the thrust is increased when magnetic moment of the coil is increased, and this characteristic is qualitatively correct as shown Eq. (1). The error bars on the thrust measurements with plasma injections are larger than the error bars on the thrust measurements without the plasma injection, likely owing to the addition of the discharge noise by the Mini-MPD arcjet. The thrust increase is measured at all condition in Fig.7. In this study, we evaluate the thrust characteristics of MPS using the thrust gain which is the ratio between the thrust with plasma injection and the thrust without plasma injection. Figure 8 shows the thrust gain at the various dynamic pressure of the Mini-MPD arcjet for different M values. As illustrated in Fig.8, for both the magnetic moment condition, the thrust gain increases with the P_{inf} increases. In addition, the thrust gain for M=2.7×10^{-5} Tm^3 is larger than M=7.1×10^{-5} Tm^3 at all P_{inf} condition. Figure 9 shows the thrust gain dependence on β_k value at P_{sw} =2.9 Pa and P_{sw} =0.34 Pa. The thrust gain at both P_{sw} condition is increased when β_{k0} increases. In this study, the β_k value is 0.0026 to 0.79, and the maximum thrust gain is 4.1. The dash line in Fig.9 is the results by the hybrid PIC simulation. The maximum thrust gain is expected at β_{k0} = 0.5; the maximum thrust gain of 4.5 is predicted approximately upper limit of the thrust gain by the numerical simulation. In higher β_k value condition (β_k>0.5), the thrust gain is decreased when the β_k increases by the hybrid PIC simulation result, for example, the thrust of MPS becomes 0 at β_{k0}~10[10,11]. The thrust saturation is experimentally observed at the high β_k condition at the injection point. The thrust gain at P_{sw}=0.34 Pa is larger than the thrust gain at P_{sw}=2.9 Pa. These results as shown Fig.8 and Fig.9 show that the thrust gain of MPS is increasing when the β_k value and P_{inf} increases and P_{sw} decreases. These results are agreement with the characteristics by the Eq. (5) and Eq. (6) that the thrust gain is depending on the $\beta_{k0}^{1/2}P_0/P_{sw}$.

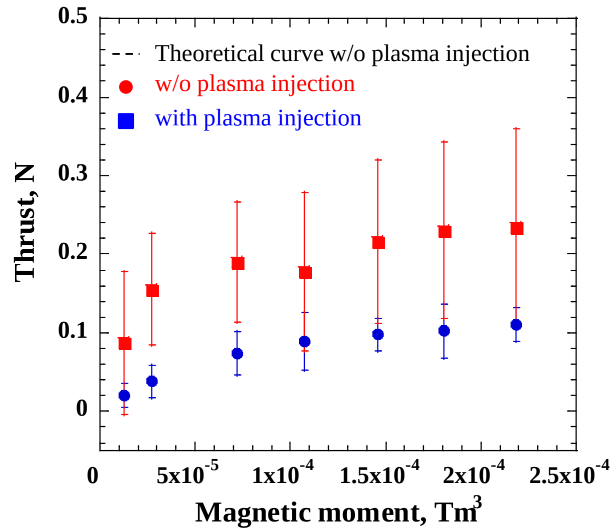


Figure 7. Thrust vs. magnetic moment in the case of with and without plasma injection. Circle marks are the thrust without the plasma injection and square marks are the thrust with the plasma injection. All data are averaged five shots. Standard deviation of each shot and fitted error is included in the error bar.

The relation between $\beta_{k0}^{1/2}P_0/P_{sw}$ and the thrust gain is shown in Fig. 10. The thrust gain is increased when $\beta_{k0}^{1/2}P_0/P_{sw}$ increases and this characteristic is qualitatively correct in this parameter range. However, the results from the laboratory experiment exhibited values smaller than those theoretically predicted. These differences are caused by n in Eq. (5). It shows that the inflated magnetic field decays according to $|B| \propto r^{-2.0}$ (n=2) since the magnetic field is frozen into the plasma jet by the ideal MHD simulation[16]. In comparison with the MHD result, the inflated magnetic field decays according to 2<n<3 since the finite ion Larmor radius effect decreases the flow of magnetic flux with respect to the flow of plasma jet[16]. Therefore, the experimental results are underestimating than the theoretically predicted in Fig.10 (n=2). In this experimental condition, $\beta_{k0}^{1/2}P_0/P_{sw}$ is about 40 to 1140, and by the other scaling parameters, this parameter is limited to 10-1000 order in laboratory experiment. In contrast, $\beta_{k0}^{1/2}P_0/P_{sw}$

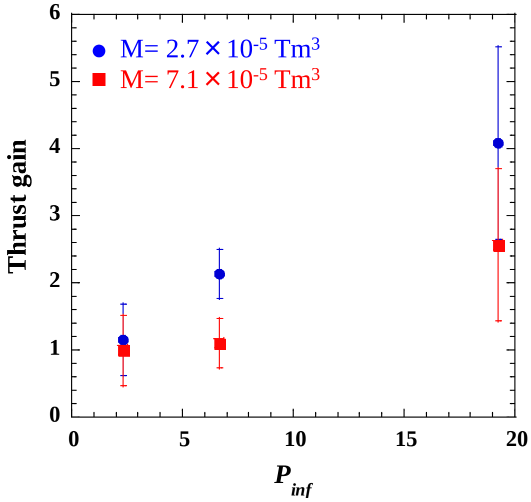


Figure. 8 Thrust gain vs. P_{inf}.

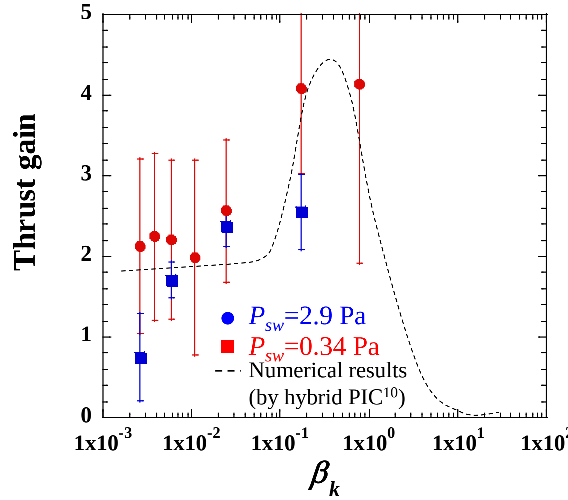


Figure. 9 Thrust gain vs. β_{k0_inf}.

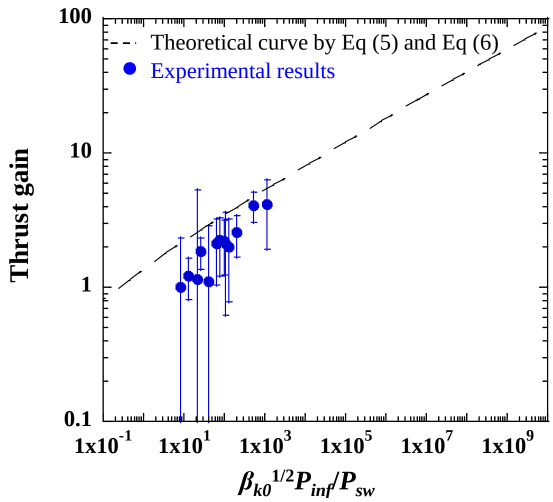


Figure. 10 Relation between thrust gain and scaling parameter of magnetosphere inflation.

is 10^7-10^9 in outer space, because the dynamic pressure of the solar wind, P_{sw}, is much smaller than the simulated solar wind in laboratory. However, from the numerical simulation, the thrust of MPS becomes 0 by high β_{k0} value injection plasma as discussed. Although the maximum β_k is 0.79 by the limitation of experimental facility, saturation of thrust gain is observed as shown Fig.9. Thus, it is seems that the application range of the scaling law by Eq.(5) is approximately β_k<1. If β_k =0.5 and n=2.3 from the hybrid simulation results are assumed ($\beta_{k0}^{1/2}P_0/P_{sw}$~$10^8$), the thrust gain of MPS spacecraft is estimated at about 20 using the superconducting coil discussed the previous work (φ3.5 m in diameter, 5000 turns, 200 A) by eq. (6)[16]. It may be necessary to experiment with larger values of $\beta_{k0}^{1/2}P_0/P_{sw}$ and to clarify the application range of the scaling law. At this time, the thrust gain with the high β_k plasma injection for magnetosphere inflation is an insufficient amount for deep space exploration. In order to improve the thrust gain of MPS, new type magnetopshere inflation methods are proposed and under studied, for example, low β_k plasma injection method[17-18]. Experimental investigation of the new magnetosphere inflation method is next step.

Conclusion

The In-space propulsion system, which we call Magnetosplasma sail (MPS), seeks to inflate a magnetosphere around the spacecraft to deflect the solar wind and pick up the large momentum from the solar wind. MPS ground simulator, consisting of a triplet MPD arcjet as the solar wind simulator (1.2×10^{18}m^{-3}, 38 km/s), the solenoid coil and the Mini-MPD arcjet as the MPS simulator (5.3×10^{19}m^{-3}, 30 km/s) has been constructed and tested in laboratory vacuum chamber. In this study, the thrust characteristics survey of MPS with plasma injection was indicated as a function of the magnetic moment M, the dynamic pressure of the injected plasma P_{inf} and the dynamic pressure of the simulated solar wind P_{sw}. It is clarified that the thrust gain which is the ratio between the thrust with plasma injection and the thrust without plasma injection is increased when P_{inf} is increased and M and P_{sw} are decreased. In addition, the thrust gain is growing both with the β_k value, but the thrust saturation was observed at the high β_k at the injection point condition (β_k~1). The maximum thrust gain in this paper was about 4.1.

Appendix

Development of Eq.(5) in this study is shown briefly. The magnetospheric size without the plasma injection is obtained as follows by the balancing of the dynamic pressure of the solar wind and the magnetic pressure.

$$n_{sw} m_i u_{sw}^2 = \frac{(2B_{mp})^2}{2\mu_0} \quad \text{(A)}$$

where B_{mp} is magnetic flux density at the magnetopause, and it is expressed using the magnetic moment, M, as

$$B_{mp} = \frac{\mu_0 M}{4\pi L_{Mag}^3} \quad \text{(B)}$$

Equation (B) is assumed to be that the coil magnetic field is decreased as r^{-3}. From Eq.(A) and Eq.(B), L_{Mag} is directly obtained as,

$$L_{Mag} = \left(\frac{M^2}{8\pi^2 \mu_0 \rho_{sw} u_{sw}^2} \right)^{1/6} \quad \text{(C)}$$

The magnetic field distribution assumes that it becomes r^n from r^{-3} by plasma injection. B_{mp} with plasma injection is expressed as

$$B_{mp} = \frac{\mu_0 M}{4\pi L_{\inf}^3} \left(\frac{L_{\inf}}{L_{MPS}} \right)^n \quad \text{(D)}$$

where L_{inf} is the distance from the coil center to the inflation point. The inflation point defined as the balance point of the dynamic pressure of injection plasma and the magnetic pressure in this model. Equation (E) is shown the magnetospheric size with the plasma injection from Eq.(A) and Eq.(D).

$$L_{MPS} = \left(\frac{2^{6/n} M^2}{(32\mu_0 \pi^2)(\rho_{sw} u_{sw}^2)^{3/n} (\rho_{\inf} u_{\inf}^2)^{1-3/n}} \right)^{1/6} \quad \text{(E)}$$

The ratio between Eq.(C) and Eq.(E) is the magnetosphere inflation rate as shown Eq.(F).

$$\frac{L_{MPS}}{L_{Mag}} = \left(2^{6/n-2} \left(\frac{P_{\inf}}{P_{sw}} \right)^{3/n-1} \right)^{1/6} \quad \text{(F)}$$

P_{inf} in Eq.(F) is the dynamic pressure of the injection plasma at the balancing point between the dynamic pressure of the injection plasma and the magnetic pressure. Equation (5) expressed Eq.(F) with the β_k value at the injection point and the dynamic pressure at the injection point.

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