Experimental and Numerical investigation of Magnetosphere inflation of Magnetoplasma sail

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Abstract: **Magnetoplasma sail which can directly convert to a thrust from the sun energy is under study. In order to develop a numerical simulation code to predict a ground experiment, comparison between the magnetospheric structure of the ground experiment and the numerical simulation is conducted. A magnetic field on an upstream side of a solar wind is measured in β=1.5×10^{-1} and β=2.04×10^{-4} using magnetic probes, where β is a ratio between dynamic pressure and magnetic pressure. The magnetosphere is expanded 20 mm in the ground experiment. A MHD model including finite magnetic Reynolds effect is employed in this study. The magnetospheric structure in the MHD simulation is substantially agreement with its the ground experiment in β=2.04×10^{-4}. This numerical simulation tool has enough potential to predict at large magnetosphere condition of the ground experiment.**

Nomenclature

A	=	area of magnetic probe, m^2
C_d	=	thrust coefficient
E	=	electric field, V/m
F	=	thrust, N
j	=	current, A
L	=	magnetospheric size, m
N	=	turn number of magnetic probe, m
n	=	number density, m^{-3}
P	=	dynamic pressure, Pa
r_c	=	radius of coil, m

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Rm	=	magnetic Reynolds number
S	=	blocking area of magnetosphere, m^2
u	=	velocity, m/s
β	=	β value ($=P/(B^2/2\mu_0)$)
μ_0	=	magnetic permeability, H/m
ρ	=	density, kg/m^3
0	=	injection point index
sw	=	Solar wind index
mag	=	Magsail index
mps	=	Magnetoplasma Sail (MPS) index

I. Introduction

Solar wind sail is one of a new type space propulsion system utilize the solar wind plasma flow.[1] One of the typical solar wind sail is Magsail converting the solar wind momentum into a momentum of a spacecraft by the interaction between the solar wind and a magnetosphere as shown Fig.1.[2] One of the characteristics of Magsail is that the thrust performance above traditional propulsion system is achievable, because Magsail doesn't need propellant on principle. Magnetoplasma Sail (MPS) is modified model of Magsail.[3] The magnetosphere of MPS is inflated by the plasma injection from the spacecraft (Fig.2). Accordingly, the large thrust is achievable even if a small coil is mounted on the MPS spacecraft. The solar wind plasma is deflected by the inflated magnetosphere by the plasma injection. The thrust of MPS is formulated as

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

where F is the thrust of MPS, C_d is a thrust coefficient, $1/2\rho_{sw}u_{sw}^2$ is dynamic pressure of the solar wind and S is a blocking area of the magnetosphere.

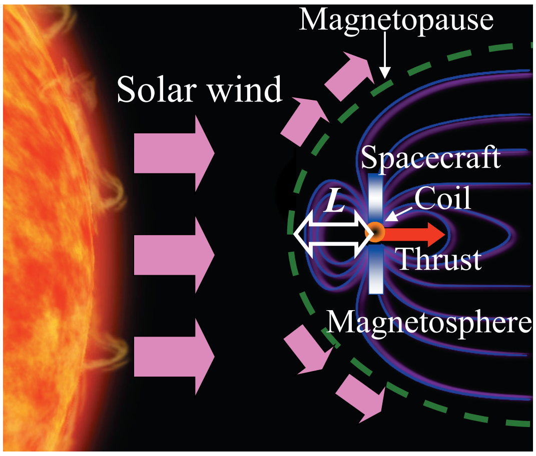


Figure 1. Magnetic sail (Magsail).

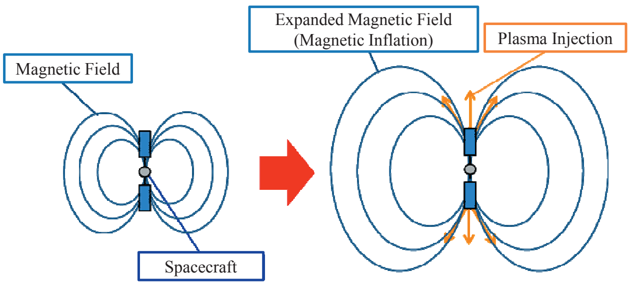


Figure 2. Magnetic inflation.

Several ground experiments and numerical simulations were conducted in previous study of MPS. The thrust generation mechanism was clarified by Ideal MHD simulation.[4] The thrust performances were obtained by MHD simulation, Hybrid PIC simulation and Full PIC simulation.[5,6,7] In the ground experiment, the magnetosphere inflation and the thrust generation were experimentally demonstrated using the MPS ground simulator at JAXA.[8,9,10] Our target thrust gain which is the ratio between the thrust of MPS mode, F_{mps}, and the thrust of Magsail mode, F_{mag}, is 100. However, the maximum thrust gain was 40 in numerical simulation and 4.1 in ground experiment. The satisfactory performance was not achieved in any study. One of factor of this issue in numerical simulations was that calculation cost of high density plasma injection condition was very high in particle simulation. The ground experiment in wide parameter range is difficult due to limitation of the experimental facility and cost although the experimental validation of the sufficient thrust performance is important. Therefore, it is necessary to obtain the optimum conditions before conducting the experiment. The MHD model including finite magnetic Reynolds is employed as prediction tool for the ground experiment in this study. The prototype of this simulation code was developed by Shizuoka University and JAXA.[11,12] Although comparison between the numerical simulation and the ground experiment was conducted by Kajimura et.al using the Hybrid PIC code, but these simulations have high calculation costs.[13] The wide parameter survey can be conducted the MHD model which is relatively low calculation cost. However, it is not revealed whether this MHD model can predict the ground experiment. The objectives are validation of the numerical model by conducting comparison with the experimental results and the numerical results.

II. Ground Experiment

A. Ground simulator

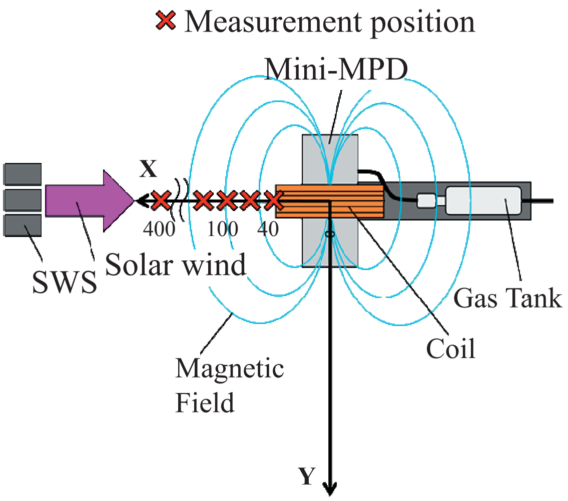
The MPS ground simulator for this study consists of the vacuum chamber (diameter: 2 m; length: 3 m), the solar wind simulator (SWS), a Magnetoplasma Sail Simulator (MPSS), a Pulse Forming Network (PFN), gas supply systems, and measuring systems.[14] A large test section (>φ1000 mm in diameter), high density (>3×10^{17} m^{-3}) and high velocity (>20 km/s) are required for the solar wind simulator. The triple quasi-steady MPD arcjet was employed as the solar wind simulator.[15] The MPSS consists of the solenoid coil (76-mm-diameter and 20-turn) and two Mini-MPD arcjets for the magnetosphere inflation. The MPSS is located at the 1250 mm from the SWS. Two Mini-MPD are adjusted in order to be same plasma parameter. All simulators operation requires high input electricity, supplied from the PFN that operates in 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.

B. Experimental Setting and Parameter

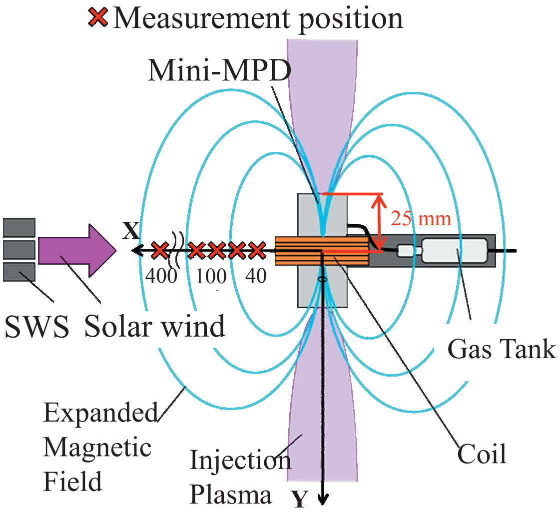
The schematic view of the magnetospheric structure measurement is shown in Fig.3. The magnetoplasma sail simulator is installed into the solar wind plasma flow. The magnetic probe is fixed on the 1-axis stage and is moved to solar wind upstream from vicinity of the coil. The measurement positions are 40-400 mm from the coil center on equatorial plane of the dipole magnetic field. The measured magnetic field is included the electromagnetic noise by operation of the Mini-MPD and the SWS. The magnetic field of MPS mode is obtained by subtracting the SWS+Mini-MPD mode from all operation modes. The magnetic field of Magsail mode without the plasma injection is obtained by the subtracting the SWS mode from the SWS+Coil mode. Table 1 shows the experimental parameters. These parameters are measured in single operation mode of each simulator. The experiment is conducted in $\beta=1.5\times10^{-1}$ and $\beta=2.04\times10^{-4}$. A β value is a ratio between magnetic pressure and plasma pressure as follow:

$$\beta = \frac{\text{Dynamic pressure}}{\text{Magnetic pressure}} = \frac{n_0 m_i u_0^2}{B_0^2 / 2\mu_0} \tag{2}$$

where n_0 and u_{sw} are the number density and the velocity of the injection plasma at an injection point. B_0 is the magnetic field at the injection point. The plasma pressure in this study is dynamic pressure because the dynamic pressure of the injection plasma from the Mini-MPD is dominant in study. The plasma parameters at the injection point are estimated by extrapolation using the measurement results near the Mini-MPD. The injection point is at 25 mm from the coil center as shown Fig.3.



(a) Magsail mode.



(b) MPS mode.

Figure 3. Experimental Setup.

Table 1. Experimental Parameter.

	high β	low β
Solar wind simulator(SWS)		
Number density [m^{-3}]	1.2×10^{18}	
Electron temperature [eV]	1.1	
Velocity [km/s]	30	
Magnetoplasma sail simulator		
Discharge current [kA]	0.28	2.0
Magnetic moment [Tm^3]	3.2×10^{-5}	2.3×10^{-4}
Magnetic field strength at coil center [T]	0.67	0.092
Number density [m^{-3}]	3.5×10^{19}	1.1×10^{20}
Electron temperature [eV]	1.1	1.5
Velocity [km/s]	14	30
β value	1.5×10^{-1}	2.04×10^{-4}

C. Measurement System

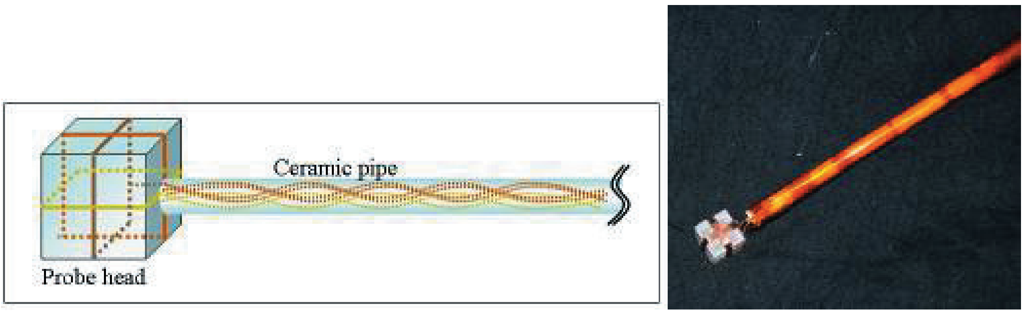
In order to measure the magnetospheric structure, the magnetic field produced by the MPS simulator is measured with a *B*-field loop magnetic probe. The magnetic field measurement system is consists of the magnetic probe, an amplifier, an oscilloscope and a PC for digital integration. The magnetic probe measuring the magnetic field consists of three-axial magnetic coils with 0.2 mm enamel wire on a small parallelepiped-shaped support (8×8×8 mm), and this is 20-turns-coil. The schematic view and the photograph of the magnetic probe are shown in Fig.4. This magnetic probe is a sensor which measures the variation of the magnetic flux and generates a voltage according to Faradays law. The voltage proportional to the variation of the magnetic field is shown follows.

$$V = -NA\left|\frac{\partial \vec{B}}{\partial t}\right| \tag{3}$$

where V is the output voltage, N is the turn number of the magnetic probe and A is an area of the coil of the magnetic probe.

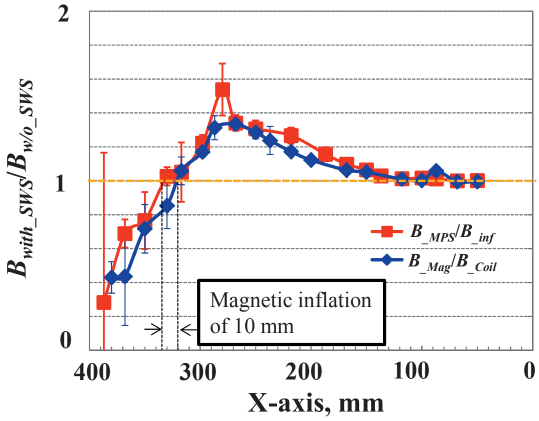
D. Experimental Results

The results of the ground experiment are shown in this section. The position of a magnetopause is identified by the ratio between the magnetic field strength with the solar wind, B_{with_SW}, and the magnetic field strength without the solar wind, $B_{w/0\_SW}$. Figure 5 shows $B_{with\_SW}/B_{w/0\_SW}$ distribution. The origin of the horizontal axis is the coil center, and the upstream side of the solar wind is large side of x-axis. $B_{with\_SW}/B_{w/0\_SW}$ is larger than unity between x=300 mm from the coil vicinity in Fig.5 (a). This reason is that the magnetic field is compressed by the interaction between the solar wind and the coil magnetic field. This region is the inner magnetosphere. On the other hand, $B_{with\_SW}/B_{w/0\_SW}$ is smaller than unity in the outer magnetosphere. The position of the magnetopause is defined at position of $B_{with\_SW}/B_{w/0\_SW}$ =1 in this study. The magnetospheric size which is the distance to magnetopause from the coil center is 320 mm in Magsail mode and 330mm in MPS mode. The magnetospheric inflation of 10 mm is obtained. Fig.8 (b) is the experimental results in β=1.5×10^{-1}. The magnetic moment is smaller than β=2.0×10^{-4} as

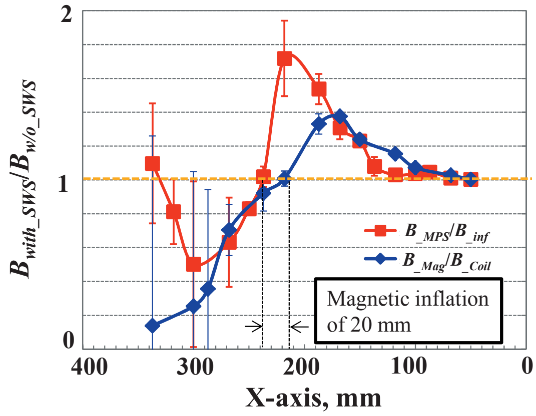


(a) Schematic View. **(b) Photograph.**

Figure 4. Magnetic probe.



(a) β=2.0×10^{-4}.



(b) β=1.5×10^{-1}.

Figure 5. $B_{with\_SWS}/B_{w/o\_SWS}$ distribution by ground simulation.

shown in Table 1. The magnetospheric size is 220 mm in Magsail mode and 240 mm in MPS mode. The magnetospheric inflation of 20 mm is obtained. The magnetic inflation is obtained in both conditions. $B_{with\_SW}/B_{w/0\_SW}$ in β=1.5×10^{-1} increases again in further than 300mm. It is caused that the noise is increased against the coil magnetic field. The peak value of $B_{with\_SW}/B_{w/0\_SW}$ in MPS mode is larger than its Magsail mode. It seems that the magnetic inflation by the plasma injection enhances compression of the magnetic field. This reason is that the solar wind particle is deflected by the injection plasma in addition to the magnetic field.

III. Numerical Simulation

A. Numerical Model

The governing equations are the MHD equation including the finite magnetic Reynolds effect. The normalized resistive MHD equations are written as follows:

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho\boldsymbol{u}\\ \boldsymbol{B}\\ E_t\end{bmatrix}+\nabla\cdot\begin{bmatrix}\rho\boldsymbol{u}\\ \rho\boldsymbol{uu}+\left(p+\dfrac{\boldsymbol{B}\cdot\boldsymbol{B}}{2}\right)\boldsymbol{I}-\boldsymbol{BB}\\ \boldsymbol{uB}\text{ -}\boldsymbol{Bu}\\ \left(E_t+p+\dfrac{\boldsymbol{B}\cdot\boldsymbol{B}}{2\mu_0}\right)-\dfrac{1}{\mu_0}(\boldsymbol{u}\cdot\boldsymbol{B})\boldsymbol{B}\end{bmatrix}+\begin{bmatrix}0\\ 0\\ \nabla\times\left(\dfrac{\boldsymbol{j}}{R_m}\right)\\ \nabla\cdot\left(\dfrac{1}{R_m}\boldsymbol{j}\times\boldsymbol{B}\right)\end{bmatrix}=-\nabla\cdot\boldsymbol{B}\begin{bmatrix}0\\ \boldsymbol{B}\\ \boldsymbol{u}\\ \boldsymbol{u}\cdot\boldsymbol{B}\end{bmatrix} \tag{4}$$

where R_m is the magnetic Reynolds number. R_m is 10 which are constant in all simulation regions in this study. The normalization of length is conducted using 1.0×10^{-3} m. The characteristic density is same order of the solar wind; 2.01×10^{-9} kg/m^3. The magnetic field is normalized by B_{mp}, where B_{mp} is the magnetic field strength at the magnetopause as shown below:

$$B_{mp}=\sqrt{\mu_0\rho_{sw}u_{sw}^2}=1.51\times10^{-3}\,[\mathrm{T}] \tag{5}$$

The resistive MHD as shown Eq. (4) is solved by the finite volume method. The numerical flux of the convective term is evaluated by the Lax-Friedrich Scheme. To extend the higher-order finite, we employ MUSCL method.

B. Numerical Setting

MPS and Magsail are simulated in the three-dimensional space. Figure 6 shows a computational grid system (63×61×61). The magnetic field in the simulation region is a dipole magnetic field in an initial condition; the dipole is located at the origin. The magnetic field in the initial condition is shown in Fig.7. The inflow boundary is set at the left side of the simulation domain. The solar wind flows to *x*-direction. The calculation is finished when the simulation is achieved steady state.

The plasma for the magnetic inflation is injected from the pole of the dipole as shown Fig.8. The divergence angle of the injection plasma is 30°. The injection position is 25 mm from the origin. The simulation parameters are shown in Table 2. The left row is the real parameter which is same parameter of the ground experiment of previous section. The right row is the non-dimensional parameter. We describe the results and discussion using the real parameter, whereas the numerical simulation is calculated using the non-dimensional parameter.

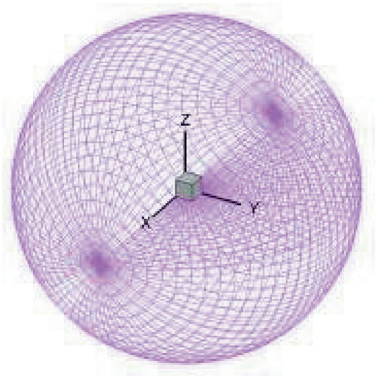


Figure 6. Simulation region of 3-D.

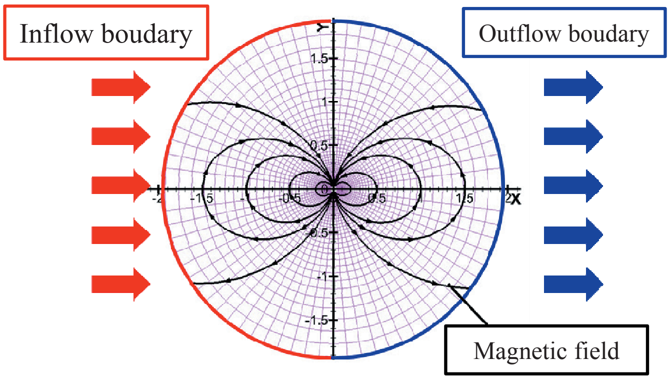


Figure 7. Initial magnetic field (x-y surface).

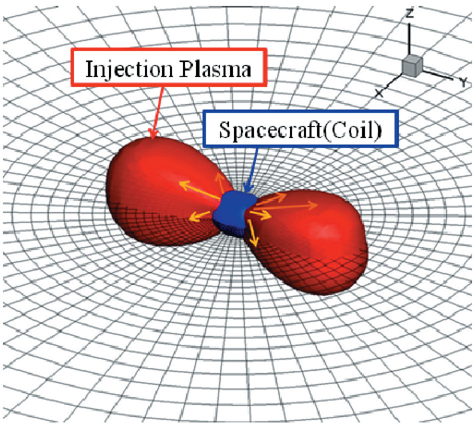


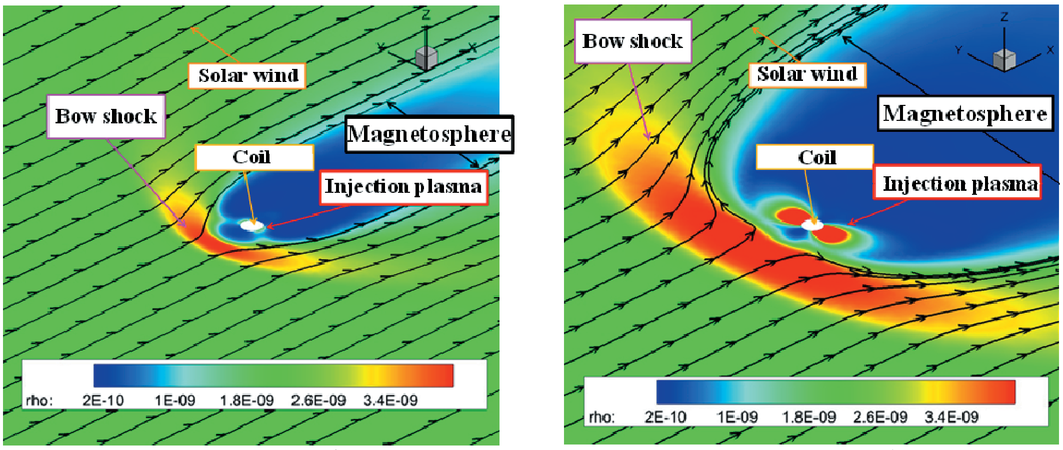
Figure 8. 3-D view of injection plasma.

Table 2. Simulation parameter.

	Simulation parameter	Nondimentional parameter
Solar wind simulator (SWS)		
Number density, n_s [m^{-3}]	1.2×10^{18}	1
Electron temperature, T_s [eV]	1.1	0.23
Velocity, u_s [m/s]	30×10^4	1
Magnetoplasma sail simulator		
$\beta=2.0\times10^{-4}$		
Number density, n_s [m^{-3}]	3.5×10^{19}	29.2
Electron temperature, T_s [eV]	1.1	0.23
Velocity, u_s [m/s]	1.4×10^4	0.5
Pressure, p_s [Pa]	12.3	13.7
Magnetic moment, m[Tm^{-3}]	2.3×10^{-4}	1.5×10^8
$\beta=1.5\times10^{-1}$		
Number density, n_s [m^{-3}]	1.1×10^{20}	91.7
Electron temperature, T_s [eV]	1.5	0.32
Velocity, u_s [m/s]	3.0×10^4	1
Pressure, p_s [Pa]	53	58.5
Magnetic moment, m[Tm^{-3}]	3.2×10^{-5}	1.9×10^7

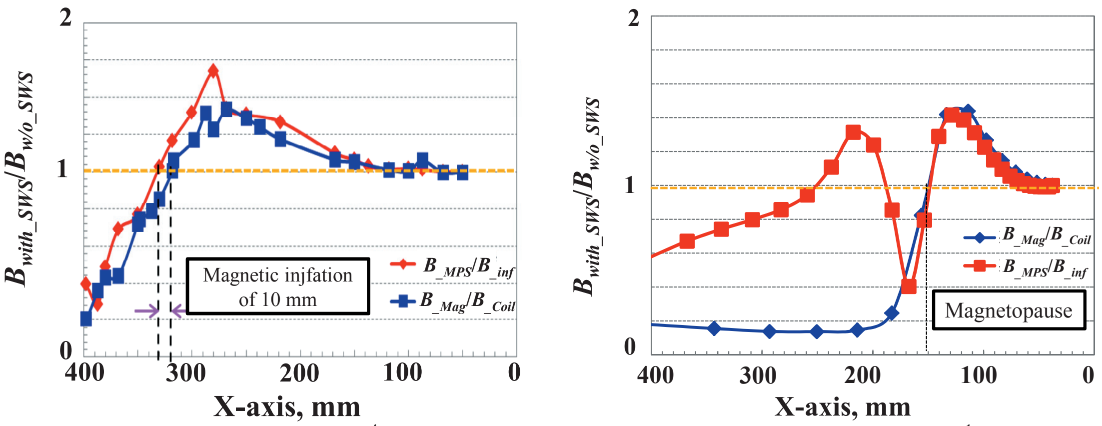
C. Numerical Results

The results of the MHD simulation are shown in this section. The flowfield, which is the counter figure of density and the stream line of the solar wind, is shown in Fig.9. Solar wind flows to *x*-direction, and the dipole is located at the origin. The magnetosphere is formed by the interaction between the solar wind and the dipole magnetic field. The plasma density is low in the magnetosphere since the solar wind plasma cannot into the magnetosphere. The bowshock is formed in front of the magnetosphere. The plasma for the magnetic inflation is injected from the vicinity of the coil, but this effect is small in β=2.0×10^{-4} as shown Fig.10 (a). In condition of β=1.5×10^{-1}, there is the high density region near the coil, and the structure of the magnetosphere is changed than β=2.0×10^{-4}. In addition, the effect of the injection plasma is conspicuous in β=2.0×10^{-4}. $B_{with\_SW}/B_{w/0\_SW}$ distribution like the ground experiment is shown in Fig.10. In condition of β=2.0×10^{-4}, $B_{with\_SW}/B_{w/0\_SW}$ distribution is almost same in Magsail and MPS mode. The magnetic inflation is not observed. In contrast, although $B_{with\_SW}/B_{w/0\_SW}$ distribution is same among the x=40 to x=150 mm in β=1.5×10^{-1}, but $B_{with\_SW}/B_{w/0\_SW}$ is increased again in x>170mm. This distribution is not observed in ground experiment. The magnetic field strength in x>170 mm is lower than the magnetopause magnetic field strength estimated by the solar wind. This region is at the bowshock. This reason is that the injection plasma flows to the bowshock and generates the opposite direction induced current to the magnetopause current. The magnetospheric size of both modes is 150 mm in Fig.10 (b). Although the magnetic inflation is not observed at the upstream side of the magnetosphere, but the magnetosphere is expanded by focusing on the perpendicular direction of the solar wind as shown Fig.9 (b).



(a) β=2.0×10^{-4}. (b) β=1.5×10^{-1}.

Figure 9. Flow field and stream line of solar wind.



(a) β=2.0×10^{-4}. (b) β=1.5×10^{-1}.

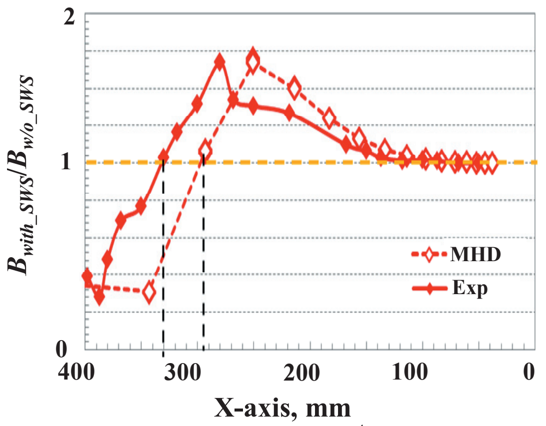
Figure 10. $B_{with\_SWS}/B_{w/o\_SWS}$ distribution by MHD simulation.

IV. Discussion

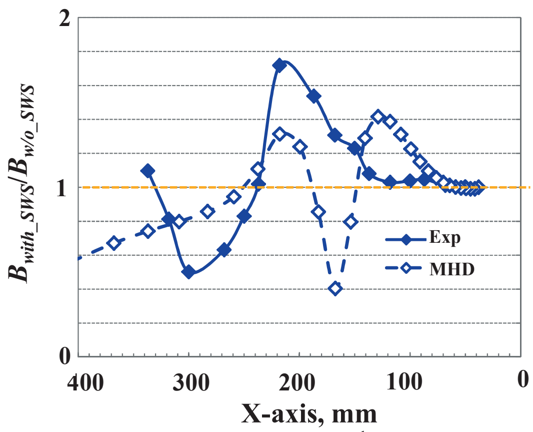
Comparison between the results of the ground experiment and the numerical simulation is conducted in this section. $B_{with\_SW}/B_{w/0\_SW}$ distribution obtained by the ground experiment and the numerical simulation are shown in Fig.11. Although the magnetospheric size in the condition of β=2.0×10^{-4} is different 20 mm, but this distribution in MHD simulation is substantially agreement with its ground experiment. In the condition of β=1.5×10^{-1}, the magnetospheric size is 150 mm in the MHD simulation and 220 mm in ground experiment. This MHD simulation cannot simulate the ground experiment in high β condition. One of the factors of this different is particle effect. The ratio between the larmor radius and the characteristics length at the magnetopause, r_{Li}/L, is used as an index of the particle effect in MPS study. r_{Li}/L is written as follows:

$$\frac{r_{Li}}{L} = \frac{m_i u / eB_{mp}}{L} \qquad \textbf{(6)}$$

where r_{Li} is larmor radius. MHD model is an approximation model of r_{Li}/L =0. r_{Li}/L in β=2.0×10^{-4} is about 0.5, and the r_{Li}/L in high β condition is over unity due to small magnetosphere. The application range of MHD model should be shown after model improvement. Another factor is the dipole approximation. This approximation is appropriate on the condition that the magnetospheric size is larger enough than the coil radius. However, if the magnetospheric size is not enough large, the coil magnetic field should be used. By these factors, the magnetic field structure numerical simulation inβ=1.5×10^{-1} is different to the ground experiment. This numerical simulation code in this study can predict the ground experiment in large magnetosphere condition (L~300 mm, r_c=72 mm and r_{Li}/L~0.5). The magnetospheric size obtained in this study is summarized in Table.3.



(a) β=2.0×10^{-4}.



(b) β=1.5×10^{-1}.

Figure 11. $B_{with\_SWS}/B_{w/o\_SWS}$ distribution of MHD simulation and ground experiment of MPS mode.

Table 3. Summary of magnetospheric size.

	Ground experiment	MHD simulation
β=2.0×10^{-4}		
Magnetospheric size of Magsail, L_{mag} [mm]	320	295
Magnetospheric size of MPS, L_{mps} [mm]	330	295
Magnetosphere inflation rate, L_{mps}/L_{mag}	1.03	1.00
β=1.5×10^{-1}		
Magnetospheric size of Magsail, L_{mag} [mm]	220	148
Magnetospheric size of MPS, L_{mps} [mm]	240	152
Magnetosphere inflation rate, L_{mps}/L_{mag}	1.09	1.03

V. Conclusion

In order to develop the numerical simulation tool to predict the ground experiment, the comparison between the magnetosphere structure of the ground experiment and the numerical simulation is conducted. In the ground experiment, the magnetospheric structure is measured in MPS ground simulator using a triplet MPD arcjet as the solar wind simulator (1.0×10^{18} m^{-3}, 30 km/s), the solenoid coil and the Mini-MPD arcjet as the MPS simulator (1.1-

3.5×10^{19} m^{-3}, 14-30 km/s). The magnetospheric size is identified by measuring the magnetic field using the magnetic probe. The magnetic inflation of 20 mm by plasma injection is obtained. The restive MHD model including finite Reynolds effect is employed as the numerical simulation model. In condition of β= 2.0×10^{-4}, the results of the numerical simulation is good agreement with the experimental results. However, the magnetospheric size is different in β= 1.5×10^{-1}. This reason is that MHD model cannot be simulated at small magnetosphere condition due to the dipole magnetic field and particle effect. In the present state, this numerical simulation tool has enough potential to predict at large magnetosphere condition (L~300 mm, r_c=72 mm and r_{Li}/L~0.5).

In the future plans, the ground experiment and the numerical simulation of more wide parameter is conducted in order to reveal the application range of this MHD code. This tool will be upgraded by including some effect, for example the local magnetic Reynolds, Hall Effect and so on.

Acknowledgments

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