Thrust Evaluation of Magneto Plasma Sail Injecting Thermal Plasma by using 3D Hybrid PIC Code

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Abstract: **Magneto Plasma Sail (MPS) is a propulsion system used in space, which generates its force by the interaction between solar wind and an inflated magnetic field via a plasma injection. In order to optimize the plasma injection parameter for increasing the thrust of MPS, a numerical evaluation has been performed by using three-dimensional hybrid particle-in-cell (PIC Code). 3 simulation models which changed the injection parameter for plasma jet and the angle of the coil were used in the present study. The best thrust performance of the MPS was founded in the 3 models.**

Nomenclature

B	=	*magnetic flux density, T*
c	=	*light velocity, m/s*
$L1$	=	*representative size of magnetosphere, m*
$L2$	=	*representative length of the magnetic field ($\|B/(\partial B/\partial r)\|$ at a local position), m*
M	=	*magnetic moment, Tm3*
MA	=	*Alfven Mach number (Alfven speed is calculated by using magnetic field at the location of L1)*
Mi	=	*Ion Mach number*
n	=	*number density, m–3*
rL	=	*Larmor radius of injected plasma (ion) at the injection point, m*
Ti	=	*ion temperature, eV*
Te	=	*electron temperature, eV*
σ	=	*momentum-transfer cross section, m2*
$\mu 0$	=	*permeability in vacuum*
ωpi	=	*ion plasma frequency, 1/s*
ωci	=	*ion cyclotron frequency, 1/s*
β	=	*local kinetic beta: the ratio of the plasma dynamic pressure to the magnetic pressure*
$\dot{m}$	=	*velocity of the injected plasma, kg/sA* = amplitude of oscillation

I. Introduction

A new space propulsion system must be rapidly developed in order to shorten mission times and to achieve high energy efficiency. In 2000, Winglee, et al.[1,2] suggested a new propulsion system, which was named Mini-Magnetospheric Plasma Propulsion (M2P2). The M2P2 spacecraft generates a large dipolar magnetic field around the spacecraft by a plasma injection. When the plasma is injected, an initial magnetic field inflates to a position where the dynamic pressure of the solar wind and the magnetic pressure, including the dynamic pressure of injecting plasma, are balanced. Then, the M2P2 spacecraft generates a propulsive force by the interaction between the extensive magnetosphere and the solar wind.

In order to estimate the propulsive force obtained by the interaction between the extensive magnetosphere and the solar wind, several investigations have been conducted using numerical simulations[3-5] and experiments in space chambers. Using a hybrid PIC simulation code, Fujita[5] has investigated the interaction between the solar wind and the dipole magnetic field (inflated magnetosphere), which has the representative length of the magnetic field ranging from 10 km to 3000 km, and he proposed an approximate formula for the drag coefficient as a function of the ratio of the ion Larmor radius to the representative length.

To feasibly evaluate the thrust of M2P2, we have to carry out a concurrent analysis that includes both the interaction between the solar wind and magnetosphere and the inflation of the magnetic field generated by the injected plasma. Omidi[6] and Khazanov[7] have conducted the numerical simulation of M2P2 using the Hybrid PIC code. Khazanov performed simulations of M2P2 with a moderately-sized coil (~10 cm) whose magnetic moment is 1.8e-3 Tm[8] using MHD and hybrid models in the near-field and the far-field from the dipole center, respectively. The evaluation of magnetic inflation was also conducted using the MHD model, whereas the process of momentum transfer from solar wind was conducted using the hybrid model. According to his study[7], although the magnetic inflation by the assistance of plasma jet occurs, the solar wind ions are not trapped in the inflated magnetosphere produced by the coil because the ion Larmor radius is significantly larger than the representative length of the inflated magnetosphere. Therefore, the thrust obtained from the M2P2 system is negligibly small. Khazanov concluded that a considerably larger plasma sail than the sail proposed by Winglee would be required.

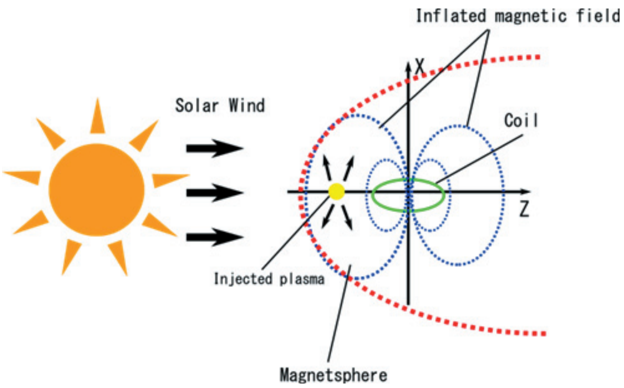


Figure 1. Conceptual illustration of MPS.

In the present paper, we aim confirmation that thrust is increased by expanded magnetosphere in an excessive ion scale. The conceptual figure of MPS is shown in Figure 1.

The principles behind thrust production in a magnetic sail are described below. On the magnetosphere boundary surface, an induction current is induced in order to achieve balance between the pressure of the magnetic field and the dynamic pressure of solar wind. According to the Biot-Savart law, this current generates a magnetic field around the coil. A Lorenz force is produced by the coil current and the generated magnetic field, which acts on the coil as a propulsive force. It has been shown that this Lorentz force can be approximated by the momentum change in the solar wind around the magnetosphere[9)]. It is assumed that trust of MPS is increased by expanded magnetosphere. Similarly the structure is. In addition, Nishida also has simulated the thrust transfer mechanism of MPS, wherein magnetic inflation is achieved by a plasma injection from the spacecraft. Within the framework of the ideal MHD formulation, if the MPS spacecraft is surrounded by a radial super-Alfvenic flow from the injected plasma, no information should be transferred upstream (i.e., to the spacecraft). This implies that the Lorentz force cannot be transferred to the MPS spacecraft[10]. In other words, the induction current induced on the magnetosphere boundary surface is cancelled by the super-Alfvenic flow of the plasma injected from the spacecraft. If this is true in an ion inertia scale, the MPS cannot produce any thrust, even if the magnetic cavity size is greatly enlarged. Hence, the paper concluded that the magnetosphere must be filled with the injected plasma whose velocity is less than the subsonic speed. According to Nishida's latest paper[11], maximum thrust can be achieved in cases where the beta of the injecting plasma βin is 2e-04 at the injection point. However, the ion Larmor radius around the magnetosphere is approximately 100 km, which is large enough so that it cannot be disregarded when compared with the representative length of the magnetic field (< 10 km). The Larmor radius of the injected plasma ions will also increase compared with the representative length of the magnetic field. Therefore, it is necessary that we perform quantitative experiments that take into consideration the influence the finite Larmor radius exerts on the propulsive force of the MPS.

In the present study, in order to confirm the thrust increment obtained by the MHD results[11] that were achieved by injecting low beta plasma, quantitative evaluations of the thrust increment produced by injecting a plasma jet with a beta less than unity were conducted by three-dimensional hybrid particle-in-cell simulations in an ion inertia scale. In these simulations, we compared the thrust values, distribution of density, magnetic field, and induced current in two cases: one including injected plasma, the other without injected plasma. The increment of the thrust generated by injecting thermal plasma with low beta is predicted quantitatively.

II. Simulation Method

The 3-D hybrid particle-in-cell model used in the present study is based on the model proposed by Harned[10]. The hybrid particle-in-cell model treats ions as individual particles and electrons as a fluid. This approach is valid when the system behavior is dominated by ion physics. The leap-frog method is adopted to solve the equation regarding the motion of the ions. We assumed a quasi-neutrality condition and set the ion charge density equal to the electron charge density. We introduced the Darwin approximation in the equation of Ampere's law. To carry out stable calculations for relatively low density plasma and strong magnetic fields, we adopted the CAM-CL (Current Advance Method and Cyclic Leapfrog) method[12]. In the vacuum region, the electric field was calculated from the Laplace equation ($\nabla^2 E = 0$) using the successive over relaxation (SOR) numerical method. Next, the digital filter was used for the electric field. We checked the code against the dispersion relation of the magnetized plasma and found our results were in good agreement with the analytical solutions. During the simulation, the electron temperature was kept constant. Cartesian coordinates (X, Y, Z) were adopted and the boundary condition used for the field quantities involved the spatial differences of the normal components being set to zero at the surface of the cylindrical simulation region in order to avoid the numerical noise of the electromagnetic field at the corner of the simulation box.

III. Simulation Model

The simulation model is illustrated in Fig. 3. The coil of the MPS is set at the center of the simulation box. The radius of the coil and the coil current are set at the values listed in Table 1. The dipolar magnetic field calculated with the set coil parameters is set in the simulation box. The parameters associated with plasma flow are set to the values listed in Table 2. Solar wind plasma is continuously added from the side of the $-Z$ boundary. The velocity distribution of the ions follows a Maxwellian distribution. After the solar wind plasma is initiated, the simulation is continued until the magnetosphere formed attains a steady-state. In the present simulation, the interplanetary magnetic field is not considered. Other simulation parameters are summarized in Table 3.

Table. 1 Coil Parameters

Coil Parameters	
Radius [km]	6.25
Current [A turn]	4
Size of magnetosphere L_1[km]	10

Table. 2 Solar Wind parameters

Solar Wind Parameters	
r_{Lsolar}/L_1	6.25
M_A	4
M_i	20
Ion inertia Length (c/ω_{pi})[km]	10

Table. 3 Simulation Parameters

Mesh number	
Particles per Cell	*6.25*
$dx[/(c/\omega_{pi})]$	*4*
$dt[/(\omega_{ci})]$	*10*

- CASE1: Injected plasma is located at the double distance of the radius of the coil from the center of the coil in the sun side.

- CASE2: Two injected plasma locations are set at the same location as CASE1 and at the opposite side as shown in Figure 3(b).

- CASE3: The magnetic moment of the coil is rotated 90degree compared with the CASE1 and 2.

Under the above three simulation models, the amount of the injected plasma mass is changed by the following three cases.

1) No injection.
2) Injected the plasma of 0.4[kg/s].
3) Injected the plasma of 0.04[kg/s] which is shown as “1/10 injection” in the present paper.

The parameters of the injected plasma in each case are listed in Table 4.

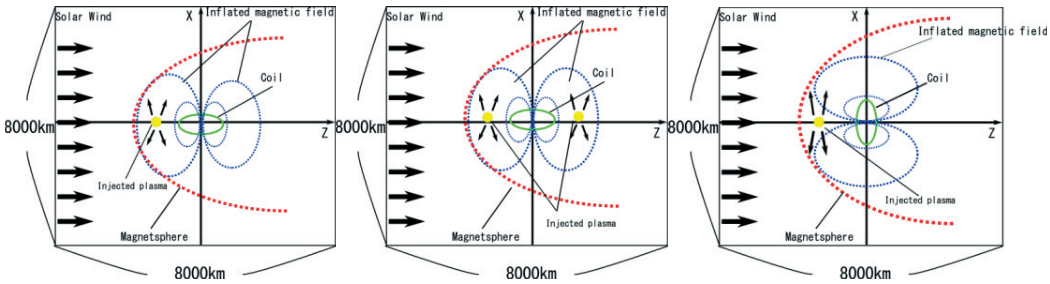


Fig. 3. a) Simulation model CASE1. b) Simulation model CASE2.c) Simulation model CASE3.

Table. 4 Injected Plasma Parameters in Simulation

	rL/L_2	T_e [eV]	T_i [eV]	β	$\dot{m}$ [kg/s]
CASE1	0.049	1	1	109.8	0.0401
CASE2	0.049	1	1	49.4	0.0401
CASE3	0.030	1	1	96.1	0.0401

IV. Simulation Results

Figure 4 shows the simulation results of the thrust in each case. Figure 5 shows the ion particle distribution and magnetic field vector for each case. Table 5 shows the thrust ratio normalized by the thrust in case for the without injected case. There was no difference of the thrust in CASE1 and CASE2. The thrust in case for the CASE1 is 1.3 times larger than that of the thrust in case for CASE3. The thrust in case for CASE2 is obtained the thrust of 3.6 times that compared without injected plasma case. Consequently, the thrust in case for CASE1 is the best method for the plasma injection in 3 cases considering the cost of increasing thrust by injected plasma.

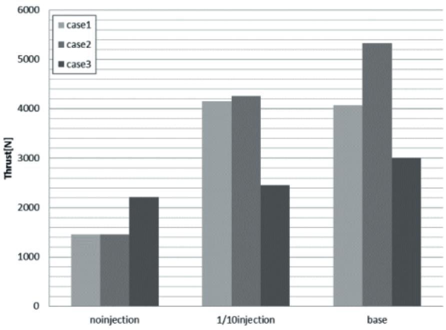
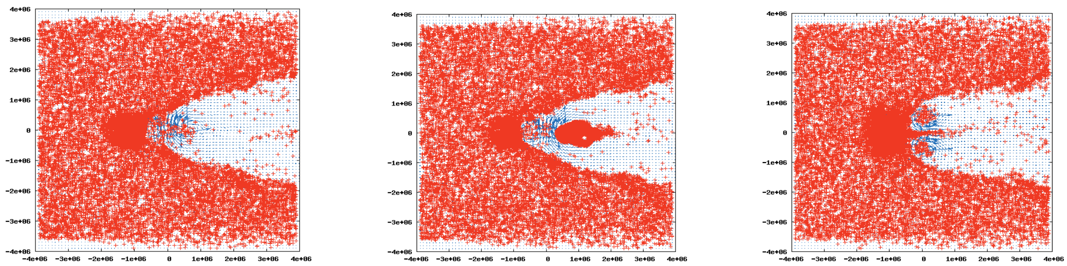


Fig. 4. Analysis result (thrust).

Table. 5. The trust ratio in each case normalized by the thrust for CASE1.

	noinjection	1/10injection	base
case1	1	2.9	2.80
case2	1	2.93	3.66
case3	1	1.11	1.36



(a) (b) (c)

Fig. 3. a) The ion particle distribution and Magnetic field vector for CASE1.
b) The ion particle distribution and Magnetic field vector for CASE2.
c) The ion particle distribution and Magnetic field vector for CASE3.

V. Summary

In the present study, the thrust of magneto plasma sail by using numerical simulation has been estimated. It was shared with 3 cases and analyzed. Consequently the thrust in case for CASE 1 is considered to be the best injection form of the three cases. The size of the coil was quite large and it was unrealistic. The size of the coil is set the realistic size and it's analyzed from now on. It's expected also to do the ground experiment in the future.

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