Numerical Study of Inflation of a Dipolar Magnetic Field in Space by Plasma Jet Injection

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A Magneto Plasma Sail (MPS) produces a propulsive force by the interaction between the solar wind and an artificial magnetic field inflated by a plasma jet injection. Using a 2D hybrid PIC simulation code, the parametric study of magnetic inflation by the plasma jet injection is performed under different realistic parameters in terms of plasma material (Ar/Xe) and injection direction. We evaluate the inflation of magnetic field when the plasma with same β_{in} is injected into a dipole magnetic field generated by a superconducting coil; the plasma is injected within an angle of 30° into the polar direction and the equator direction. It is found that when the Ar plasma (β_{in} = 5) is injected into the polar direction, the magnetic field decays in the polar direction according to $B \propto r^{-2.1}$ and when the Ar plasma (β_{in} = 5) is injected into the equator direction, the magnetic field decays in the polar direction according to $B \propto r^{-1.8}$.

Keywords: magneto plasma sail, magnetic inflation, hybrid PIC simulation

1. Introduction

A deep space exploration mission has been proposed for discovering new space physics and investigating many attracted planets. If we plan to go on a deeper space, we require a longer time and more propellant. Therefore, a new space propulsion system must be rapidly developed in order to shorten the mission time and achieve high energy efficiency.

In 2000, Winglee, et al. [1] suggested a new propulsion system which name was the mini-magnetospheric plasma propulsion (M2P2) system. The M2P2 spacecraft generates a large magnetic field around the spacecraft by a plasma injection. When the plasma is injected, the 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 spacecraft can obtain the propulsive force by the interaction between the extensive magnetosphere and the solar wind.

We formed a research group in order to realize the magneto plasma sail (MPS) which is based on the design parameters of the M2P2. Our research group has proposed a new design of the MPS and a space mission [2]. For MPS research, there are two important issues. One is the thrust prediction obtained 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 by using numerical simulations and experiments in space chambers [3-5]. The other is qualitative and quantitative evaluations of the magnetic inflation by injecting plasma into a dipole magnetic field generated by a superconducting coil. In the present paper, the latter issue is addressed.

In the past researches of magnetic inflation, by using the MHD simulation code, Nishida, et al. [6] have conducted qualitative and quantitative evaluations of the magnetic inflation. According to the parameters used in the simulation of magnetic inflation, the MHD approximation is valid in the near field around the injection point since the strength of the magnetic field is significantly large. This implies that the Larmor radius (r_L) of injected ions (Ar) is sufficiently smaller than the representative length (L) of magnetic field, which corresponds to the radius of the coil. On the other hand, in the far field from the injection point, the ion kinetic effect should be taken into account by using a hybrid model since the r_L increases and r_L/L becomes grater than one.

Winske et al. firstly performed a fully hybrid simulation of the magnetic field inflation process by injecting a plasma jet from the dipole center under the condition $r_L/L<1$ and $r_L/L>1$ [7]. The results of their simulation indicate that if r_L/L is less than unity, the magnetic field is inflated, while if r_L/L is grater than unity,

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the magnetic inflation does not occur because the injected ions are not trapped by the magnetic field. We also evaluated the inflation of magnetic field by using a 2D hybrid PIC simulation code when Argon (Ar) plasma with different β_{in} including the value less than one is injected into the dipolar magnetic field generated by a superconducting coil [8]. (β_{in} : the ratio of the dynamic pressure of injected plasma to the magnetic pressure at the injection point.) In that simulation, the magnetic field inflated by the plasma injected within an angle of 30° into the polar direction. And it was found that the magnetic field decayed in the polar direction according to $B \propto r^{-2.4}$ after the plasma (β_{in} = 0.1) was injected. Otsu and Nagata performed such simulation by using a MHD code for several β_{in} values [9]. They concluded that in order to obtain a higher performance of the MPS than that of other electric propulsion systems, it was necessary to inject the plasma with a low β_{in} value of less than unity, typically, 10^{-6}. According to our past research results [8], the expected decay index of inflated magnetic field in case with low β_{in} plasma injection from 10^{-2} to 10^{-6} will be less than -2.4.

In the present study, the quantitative evaluation of magnetic inflation of the magnetic field by injecting plasma under different realistic parameters in terms of plasma material (Ar/Xe) and injection direction (polar and equator) are investigated including ion kinetic effect by using a hybrid particle-in-cell code. The density of background plasma (solar wind: 10^6 [m^{-3}]) is absolutely lower than that of the plasma jet (10^{20} [m^{-3}]). So the background plasma is neglected and the plasma jet assumes to be injected into a vacuum. The ion Larmor radius (r_L) of the plasma jet is smaller than the representative length (L) of the dipole magnetic field, the value of r_L/L is 0.1 in the near field of the injection point. As the injected ions move to the far field from the injection point, r_L increases; therefore, r_L/L gradually increases from 0.1 to 1 and beyond. In the present simulation, this transition range of r_L/L is also considered.

2. Simulation Model

An example of the MPS spacecraft is shown in Fig. 1. An arcjet system for injecting plasma is located at the center of the spacecraft. The radius of the superconducting coil is 1.0 [m] and the coil current is 1.6×10^4 [A・turn]. The plasma is injected within an angle of 30° into negative and positive polar or equator directions. The simulation model adopted in this study is shown in Fig. 2 (polar injection) and Fig. 3 (equator injection). The coil is located at the origin of the simulation model and it generates the dipolar magnetic field. The grid size is set to be around ion inertia length in both r- and θ-direction. Initially, the ions are injected within an angle of 30° into the polar and equator direction. They are located randomly and injected from a region with a finite thickness calculated by V × Δt (velocity of the injected plasma × time step size) in each time step. This injected region is located at a distance of 1.0 [m] from the center of the coil. The total particle number is 6.0×10^6, this corresponds to put about 4.4×10^4 particles in each cell. Each particle represents 1.3×10^{14} of real ions. The density and velocity of the injected plasma (Ar) for β_{in} of 5.0 are N = 3.75×10^{20} [m^{-3}] and V = 4.0 [km/s], respectively. This velocity corresponds to an Alfven Mach number of 2.25. There is no plasma including solar wind in the initial background. The strength of the magnetic field at the injection point is 0.01 [T], which corresponds to β_{in} value of 5.0. The temperature of the ions is 1 [eV] and they have a Maxwellian velocity distribution.

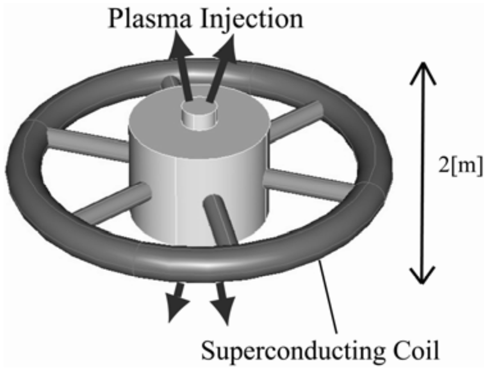

Fig.1 An example of the MPS spacecraft

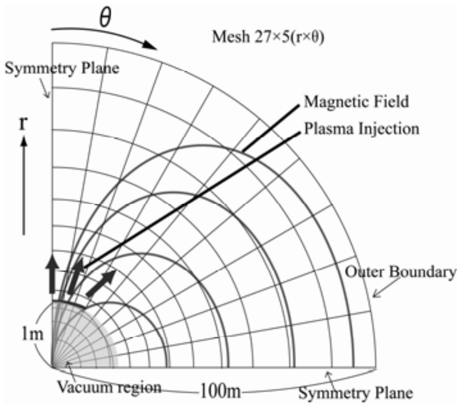

Fig.2 Simulation model (polar injection) and grid image.

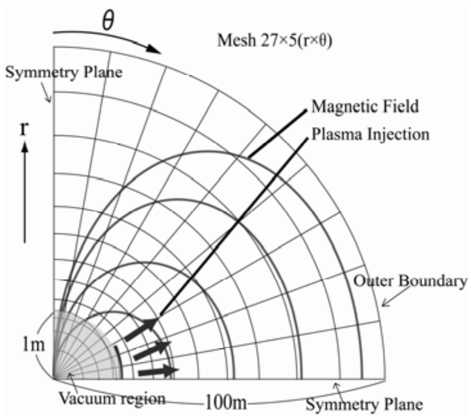

Fig.3 Simulation model (equator injection)

Table.1: Simulation cases and Parameters

Case name	Plasma	Injection	Velocity [m/s]	density [/m^3]	r_L/L	β_{in}
CASE1	Ar	Polar	4000	3.75E+20	0.17	5.0
CASE2	Ar	Equator	4000	3.75E+20	0.17	5.0
CASE3	Xe	Polar	4000	1.13E+20	0.55	5.0
CASE4	Xe	Polar	1221	1.22E+21	0.17	5.0
CASE5	Xe	Polar	2201	3.75E+20	0.30	5.0

The temperature of electrons is 4 [eV] (constant). The electrical resistivity is set to zero and the zero-gradient condition is adopted at the outer boundary shown in Fig. 2 and Fig. 3.

3. Simulation Parameters

The simulation cases and parameters are listed in Table 1. In CASE1 and CASE2, the Ar plasma is injected with same β_{in} of 5.0 within an angle of 30° into the polar direction (CASE1) and equator direction (CASE2). In CASE3, CASE4 and CASE5, the Xe plasma is injected with same β_{in} of 5.0 within an angle of 30° into the polar direction. In CASE3, the velocity of injected plasma is the same value of CASE1 (Ar injection case). In CASE4, the r_L/L is the same value of CASE1. In CASE5, the injection density is the same value of CASE1. The purpose of this parametric study is to clarify the difference of the decay index of inflated magnetic field among different injection parameters under the same β_{in}.

After the plasma injection was initiated, the simulation was continued until the inflated magnetic field reaches a steady-state. Since the magnetic field (B : B_r in polar direction of dipolar magnetic field) decays according to $B \propto r^n$, the value of n in the polar direction was estimated from the steady-state result of the simulation in each case. The initial magnetic field decays according to $B \propto r^{-3.0}$ and the value of n will increase after the plasma is injected.

4. Simulation Code

Based on the 3D hybrid code [10], a new 2D hybrid code has been developed for the simulation of the magnetic field inflation process. The code utilizes the spherical coordinate system and the condition, $\partial/\partial\phi = 0$. A variable size of grid is used to reduce the calculation cost in the evaluation of the magnetic inflation over a wide range from the near field (few meters) to the far field (few tens of meters).

The hybrid code treats ions as individual particles and electrons as a fluid. This approach is valid when the system behavior is dominated by the ion physics. The leap-frog method is adopted to solve the equation of motion of the ions. We assume quasi-neutrality and set the ion charge density equals to the electron charge density. We apply the Darwin approximation to the equation of Ampere's law. The CAM-CL method [11] is adopted for performing a stable calculation in relatively low density plasma and in a strong magnetic field. In vacuum region, the electric field is calculated by the Laplace equation ($\nabla^2 E=0$).

5. Simulation Results

Figure 4 shows a plot of the initial magnetic field line. Figure 5 shows plots of the magnetic field line and ion particles distribution at t = 95 ω_{ci}t for CASE1 and CASE2. In each case, the structure of the magnetic field changes and stabilizes at t = 95 ω_{ci}t. In each figure including Fig. 4, the magnetic field line which is marked with an arrow

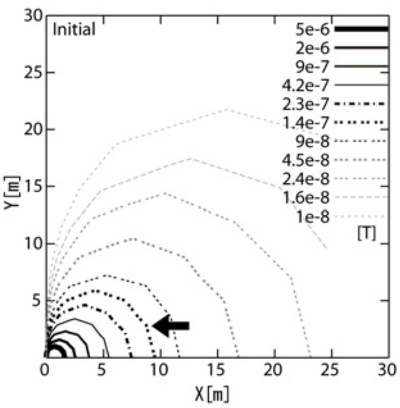

Fig.4 Plot of initial magnetic field line.

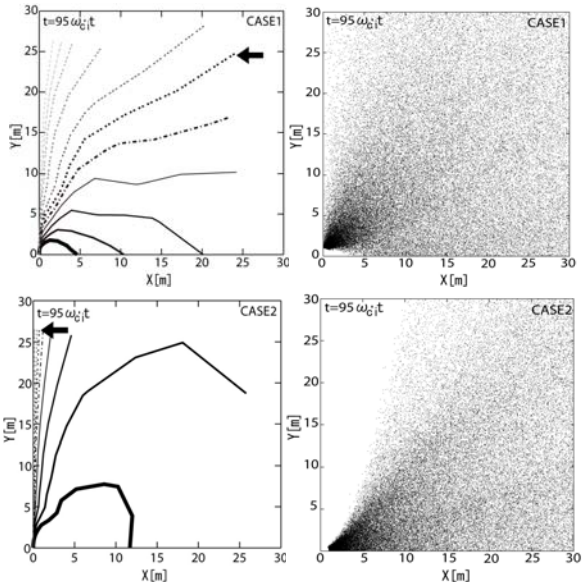

Fig.5 The magnetic field line and ion particles distribution at t = 95 ω_{ci}t for CASE1 and CASE2.

indicates the same intensity. The magnetic field line in CASE2 of the equator injection reaches in far position as indicating the arrow and the magnetic field is inflated stronger than that of CASE1 of the polar injection. In CASE2, the plasma is injected into the equator direction as shown in the right side figure of Fig. 5. The angle between the vector of the magnetic field and the direction of injected plasma is almost perpendicular. So the intensity of v×B (ions velocity×magnetic field) in CASE2 which is the cross product in an equation for calculation of electric field is larger than that of CASE1. Consequently, $E\varphi$ which is generated by the r- and θ- components of higher velocity of ions and the magnetic field (E=v×B) becomes larger. Figure 6 shows the contour plot of the generated $E\varphi$ in near injection region. The generated $E\varphi$ strengthens the r- and θ- components of dipolar magnetic field at the position where the injected plasma exists, and it causes the magnetic inflation.

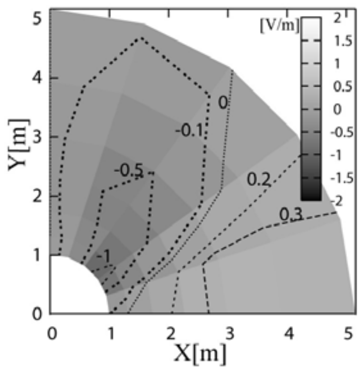

Fig.6 The contour plot of E_φ at t = 10 ω_{ci}t (CASE1).

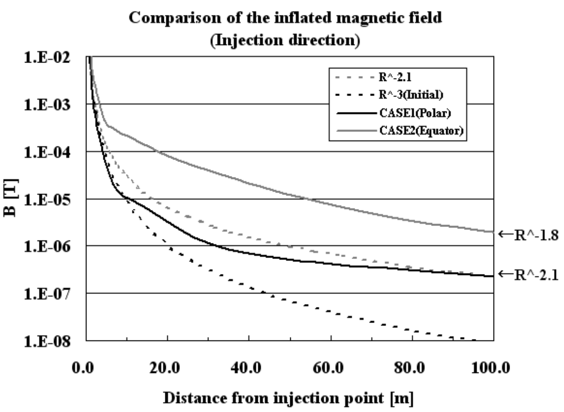

Fig.7 The intensity of the magnetic field at t = 95 ω_{ci}t along the polar axis for different injection direction (CASE1 and CASE2).

Figure 7 shows the intensity of the magnetic field along the polar axis for different injection direction (CASE1 and CASE2). The dashed black line represents the initial magnetic field. The dashed gray line represents the line of $B \propto r^{-2.1}$. As shown in Fig. 5, the magnetic field in CASE2 of the equator injection is inflated stronger than that of CASE1 of the polar injection. In these two cases (β_{in}=5.0), r_L/L is less than 0.1 at the injection point. This condition is necessary for magnetic inflation [7]. After the plasma is injected, r_L/L increases significantly. The magnetic field in the polar direction decays according to $B \propto r^{-2.1}$ when the plasma is injected into the polar direction and $B \propto r^{-1.8}$ when the plasma is injected into the equator direction.

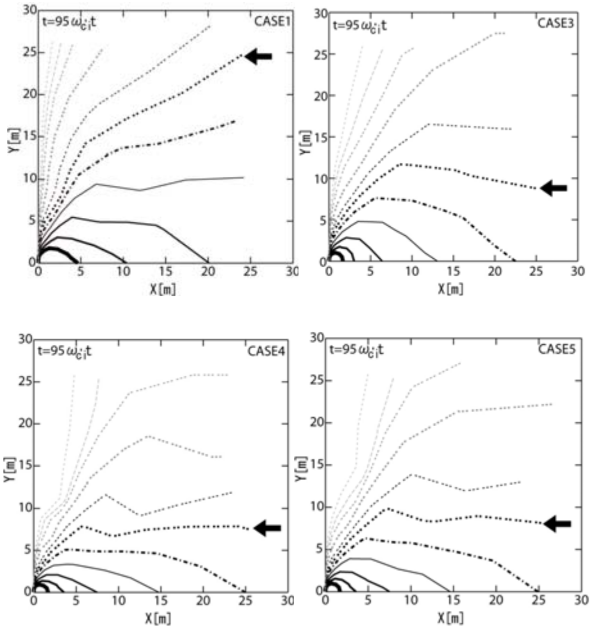

Fig.8 The magnetic field line at t = 95 ω_{ci}t for CASE1, CASE3, CASE4 and CASE5.

Figure 8 shows the magnetic field line at t = 95 ω_{ci}t for CASE1, CASE3, CASE4 and CASE5 respectively. The plasma kinetic energy of injected plasma in all cases is the same value since the value of β_{in} is the same. The magnetic field line in CASE1 of the Ar injection reaches in far position as indicating black bold arrows and the magnetic field inflates stronger than that of CASE3, CASE4 and CASE5 of the Xe injection with the same β_{in}. Under the same β_{in}, if the injection velocity of ion is fixed, higher density of Ar plasma compared with the density of Xe can inject since the atomic mass of Xe ion is larger than that of Ar ion. As the density of injected plasma becomes higher, the electric field generated by the electron pressure gradient is larger. The ions are then accelerated strongly by the large electric field, and consequently, $E\varphi$ generated by r- and θ- components of accelerated ions and magnetic field (v×B) becomes larger. The generated $E\varphi$ strengthens the dipolar magnetic field at the position where the injected plasma exists, and it causes the magnetic inflation. Therefore, a higher density value is effective in inflating the magnetic field.

In CASE 4 and CASE5, the injection velocity of Xe ion is smaller than that of Ar in CASE 1. As the velocity of injected plasma becomes higher, as we mentioned before, Eφ generated by the r- and θ- components of accelerated ions and magnetic field (v×B) becomes larger. The generated Eφ strengthens the dipolar magnetic field at the position where the injected plasma exists, and it causes the magnetic inflation. In CASE3, CASE4 and CASE5, the Xe plasma is injected with same β_{in}, but with different injection velocity, injection density and r_L/L in the injection point, respectively. The slight difference of the configuration of the magnetic field among results of these cases shown in Fig. 8 can be seen.

Figure 9 shows the intensity of the magnetic field along the polar axis at t = 95 ω_{ci}t for CASE1, CASE3, CASE4 and CASE5. The dashed black line represents the initial magnetic field. The dashed gray line represents the line of $B \propto r^{-2.2}$. The magnetic field in the polar direction decays according to $B \propto r^{-2.2}$ when the Xe plasma with velocity of 4000 [m/s] is injected into the polar direction in CASE3 . And in CASE4 and 5, the magnetic field in the polar direction decays according to $B \propto r^{-2.3}$ and $B \propto r^{-2.27}$, respectively. This slight difference of decay index among CASE3, CASE4 and CASE5 is caused by the injection velocity of the Xe plasma.

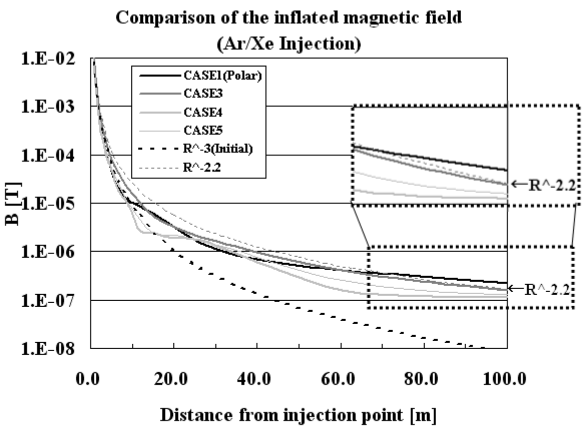

Fig.9 The intensity of the magnetic field at t = 95 ω_{ci}t along the polar axis for CASE1, CASE3, CASE4 and CASE5.

6. Summary

In the present study, the numerical simulation of the magnetic inflation, which is one of the key issues in MPS researches, is performed by using the 2D hybrid code with the spherical coordinate system and considering the ion kinetic effect. The parametric study of the magnetic inflation is performed under different realistic parameters in terms of plasma material (Ar/Xe) and injection direction with same β_{in} value. And then, we perform the quantitative evaluation (decay index) of the magnetic inflation and clarify the inflation mechanism to realize the effective inflation of the magnetic field.

In contrast to the initial magnetic field that decays according to $B \propto r^{-3.0}$, the magnetic field in the polar direction decays according to $B \propto r^{-2.1}$ when the Ar plasma is injected into the polar direction and $B \propto r^{-1.8}$ when the same plasma is injected into the equator direction.

The magnetic field inflation is caused by Eφ that is generated by the r- and θ- components of v×B (the cross product of the velocity of the accelerated ions and the magnetic field). The rotation of this Eφ is equal to the time derivation of the r- and θ- components of magnetic field. Generated Eφ strengthens the dipolar magnetic field at the position where the injected plasma exists, it causes the magnetic inflation.

In order to realize a mission by using MPS, it is necessary to achieve the magnetic inflation by injecting plasma jet with the beta value typically 10^{-6}. In case of lower β_{in} plasma, there is a possibility to excite the slow magnetosonic wave. This wave is excited in shorter time scale compared to the time scale of excitation in higher β_{in} plasma if the wave number is the same. Generally, if some kind of waves can be excited in the injected plasma, the structure of inflated magnetic field in any β_{in} plasma is speculated to be not simple dipolar field. So we need to investigate the influence of excitation of wave on the thrust obtained by MPS.

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