Numerical Simulation of Plasma Behavior in a Magnetic Nozzle of a Laser- plasma Driven Nuclear Electric Propulsion System

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Abstract. Numerical simulations of plasma behavior in a magnetic nozzle of a Laser- Plasma Driven Nuclear Electric Propulsion System are conducted. The propellant is heated and accelerated by the laser and expanded isotropically. The magnetic nozzle is a combination of solenoidal coils and used to collimate and guide the plasma to produce thrust. Simulation calculations by a three-dimensional hybrid code are conducted to examine the plasma behaviors in the nozzle and to estimate the thrust efficiency. We also estimate a fraction (α) of plasma particles leaking in the forward (spacecraft) direction. By a combination of a few coils, we could decrease α value without degrading the thrust efficiency. Finally, the shaped propellant is proposed to increase the thrust efficiency.

Keywords: Magnetic Nozzle, Nuclear Electric Propulsion System, 3D hybrid code

INTRODUCTION

A deep space exploration mission has been proposed by many researchers in major countries of the world for discovering new space physics and investigating some attracted planets. These missions have revealed that if we plan to go on a deeper mission, we require a longer time and more propellants. Therefore, a new space propulsion system must be rapidly developed in order to shorten the mission time and achieve high energy efficiency. As one of candidates of next-generation electric propulsion system for future interplanetary transport system, a laser-plasma driven nuclear electric propulsion system has been proposed. The output of an electric power supply of this system does not depend on the distance from the solar since this propulsion system equips with the nuclear power plant as the electric power supply. So, it is an attractive candidate for future interplanetary transport system since it could provide both large specific impulse and power. The method for generating thrust power of this system uses a magnetic nozzle. This magnetic nozzle is composed of solenoidal coils and used to collimate and guide the plasma to produce thrust. The nozzle concept would provide advantages in that the plasma would not contact wall structures directly when exhausted from the nozzle.

Our research group has been proposing the design of this system by using the energy of Laser Fusion instead of simple Laser-Heating Plasma like this system as shown in Fig. 1 and studying the performance and the feasibility of this system[1]. This propulsion system has a magnetic nozzle which can control the expanding plasma flow accelerated by the high intensity laser and can generate a propulsive force. So far, several estimations of thrust efficiency of the magnetic nozzle have been conducted. The current of coil and the size of coil are optimized for obtaining the high thrust efficiency. Nagamine and Nakashima simulated plasma behaviors and calculated thrust efficiency of a magnetic nozzle by using a three-dimensional (3D) hybrid code for one coil system, and examined how the thrust efficiency varies with certain parameters[2]. Sakaguchi et al., by using the same simulation code, have investigated the behaviors for two-coil systems[3]. Kajimura et al. examined how a thrust vector varies with changing positions of the fusion explosion (off-axis explosion)[4]. Recently, Matsuda et al. have examined the effects caused by shaping the target propellant by using a combination of smoothed particle hydrodynamics code and the hybrid code[5].

These numerical researches used the parameters of scale-down model instead of realistic parameters of Laser Fusion Rocket. The physical phenomena in the magnetic nozzle depends on the scale of ion gyro motion and the ratio of the energy of magnetic field to the kinetic energy of plasma, so if we take care of such dimensionless parameters, these past results can be applied to the behavior of plasma with lower energy generated by this Laser-plasma Driven Nuclear Electric Propulsion System (NEP). Figure 1 shows a schematic illustration of the NEP proposed. A small nuclear reactor is used to obtain electricity and to drive a ceramic laser. A plastic pellet is irradiated by the laser to produce plasma in a magnetic nozzle. The nozzle here is composed of multiple magnetic coils to increase the redundancy against the failure of the single coil, resulting in the increase of system reliability. We note that the neutron shield against the coil is not required here since no fusion reaction is occurring in the nozzle.

This Nuclear Electric Propulsion System have some issues to be solved, one of them is to protect the spacecraft against the high energy plasma accelerated by the laser. If the magnetic nozzle is generated by only one coil, the high energy plasma accelerated by the laser will leak into the spacecraft direction and damage the spacecraft. To eliminate this high energy plasma coming through the center of the coil and to avoid a bad influence to the spacecraft, a new configuration of magnetic nozzle is needed. We also have been discussing the required thrust efficiency in the case of increased number in the coil for generating magnetic field. If we use two coils for generating magnetic nozzle, the required thrust efficiency is at least 80% in the case of the Laser Fusion Rocket[6]. So, in the case of the Laser- Plasma Driven Nuclear Electric Propulsion System, we also must take the thrust efficiency into consideration to increase the reliability of total rocket system. In this paper, we show the simulation results of the plasma behavior and estimation of the thrust efficiency in the new coil configuration by using a three-dimensional (3D) hybrid code. Then, in order to control the expanding plasma accelerated by the laser and to increase the plasma contributing the thrust, the shaped target is proposed. We also, by using the 3D hybrid code, will show the simulation results of the plasma behavior and estimation of the thrust efficiency for this shaped target and new coil configuration. Then, the feasibility of new coil system and the use of shaped target are discussed.

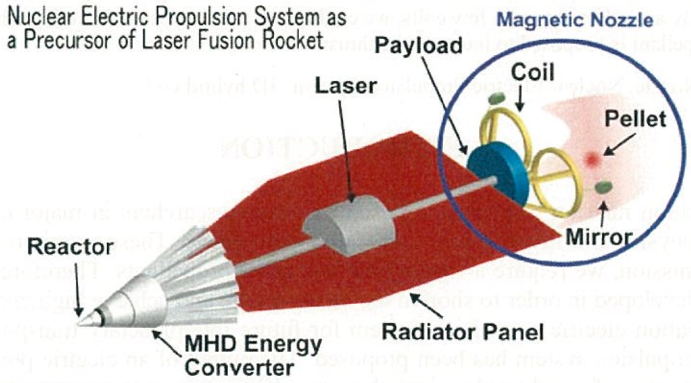


FIGURE 1. Schematic of the nuclear electric propulsion system proposed

SIMUATION AND EVALUATION METHODS

To calculate the plasma behavior in the magnetic nozzle, we have developed a 3D hybrid code based on the model given by Horowitz[7]. 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 equal to the electron charge density. We apply the Darwin approximation in the equation of Ampere's law. The predictor-corrector method for field solver is adopted. In the simulation, the electron temperature is constant. The zero-gradient condition is adopted as the boundary condition. Calculation models are based on the configurations used in a laser fusion rocket[3]. Calculation parameters tentatively adopted are the same as given in Ref.3: coil radius is 1.0m, coil current 3.57 MA, and plasma initial radius of 0.3m with its energy of 4MJ. In this case, the ratio of plasma kinetic energy to the energy of the magnetic field is around 0.5. The calculation time is 11.08[μs] which corresponds to around $210\omega_{ci}t$. A number of particles simulated is 100000.

The following two values for evaluation are defined. One is the thrust efficiency η defined by equation (1) and the other is α defined by equation (2) which is the ratio of the ions leakage into the spacecraft (- Z) direction to the total amount of ions.

$$\eta = \frac{\Sigma\, m v_Z\,(\,momentum\ :\ z - direction\,)}{\Sigma\, m \left| v_0 \right| (\,momentum\ :\ initial\,)} \qquad (1)$$

$$\alpha = \frac{(\,number : -z - direction)}{(\,number : tatal\,)} \qquad (2)$$

SIMULATION MODEL AND RESULTS

Simulation model of Twin-coils System (case1) and Results

In our past researches, in order to optimize the thrust efficiency, the radius of coils and current of coils were changed parametrically. In the two coils system, the centers of these two coils were located on the same z-axis. So, it was difficult to reduce particles leakage into the spacecraft (- Z) direction and these particles could damage the spacecraft. In the present research, some new coil configuration is proposed to decrease such particles. The coil configuration of case 1 taken up here is shown in Fig. 2. Two coils are arranged side by side with the distance of 2.3m, and the plasma is located at midpoint between these coils to reduce particles leakage into the spacecraft (- Z) direction. The magnetic nozzle here is composed of two magnetic coils to increase the redundancy against the failure of the single coil, resulting in the increase of system reliability. Calculation parameters associated with coils are referred in the previous section. The results of ion particles distribution and vector plot of magnetic field are shown in Fig. 3(a) (initial, Z-X plane) and Fig. 3(b) (t=11.08 μsec, Z-X plane). The magnetic field acts like a spring to push back the expanded plasma. A part of the expanded plasma moved in the –Z direction across the center of the magnetic nozzle. This is because the same current are given in two coils and the magnetic field generated by each coil is canceled at the center of the magnetic nozzle. The resulting values for η and α are 74 and 3.0 %, respectively. It is found that the plasma tends to expand along Y– axis. This results in reduction of the thrust efficiency.

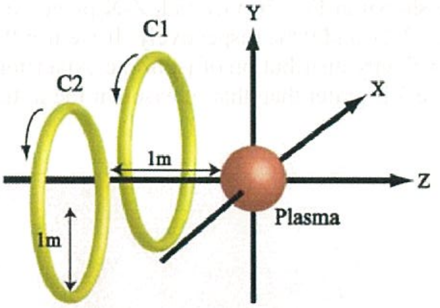
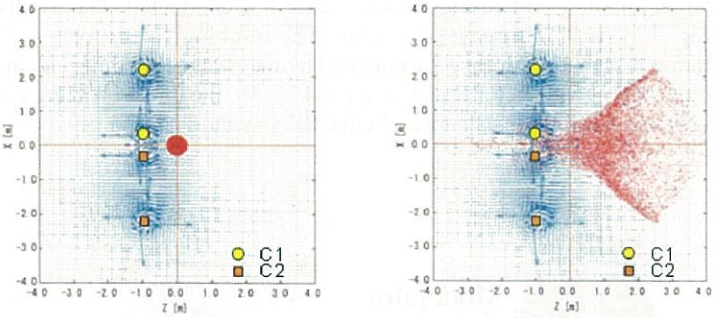


FIGURE 2. Simulation Model (case1)



(a) (b)

FIGURE 3. Ion particle distribution and vector plot of magnetic field, (a) initial, (b) t=11.08[μsec]

Simulation Model of Three-coils System (case2) and Results

In order to reduce particles leakage into the spacecraft (- Z) direction, a new coil configuration is proposed as case 2 shown in Fig.4. This is a special combination of three coils, the coil C2 is added in the previous coil configuration for case1. The initial plasma which has the isotropic expansion velocity is located at x=1.15[m]. The results of ion particles distribution and vector plot of magnetic field on Z-X plane are shown in Fig. 5, for (a) t=11.08[μsec], and (b) t=22.16[μsec]. It is showing that the plasma particles leaking along the axis return back through another C2 coil. Thus, α value decreases to zero with η value of 73 %. This coil configuration can be achieved to protect the spacecraft against the high energy plasma accelerated by the laser.

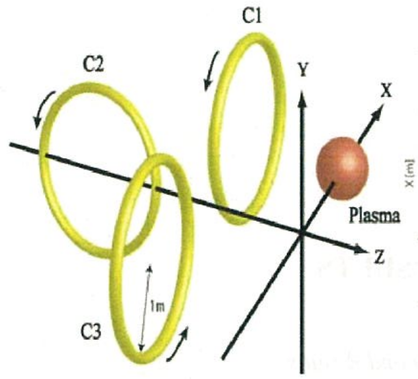
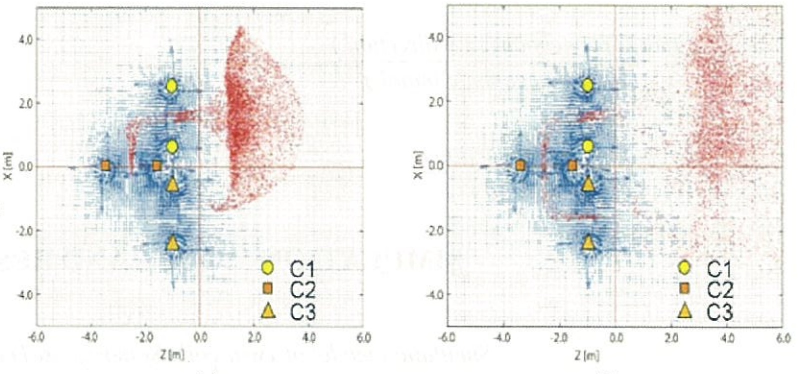


FIGURE 4. Simulation Model (case2)



(a) (b)

FIGURE 5. Ion particle distribution and vector plot of magnetic field, (a) t=11.08[μsec], (b) t=22.16[μsec]

Simulation Model of Three-coils System Using Shaped Target (case3) and Results

In order to control the expanding plasma accelerated by the laser and to increase the plasma contributing to the thrust, the shaped target is proposed as shown in Fig. 6. The shaped target is made of a core plastic pellet and the pellet is surrounded by a moderator (propellant). Plasma generated by laser energy in the pellet collides with the moderator to produce larger plasma. When the moderator is shaped by cutting the part of the moderator in a direction of magnet coil that composes a magnetic thrust chamber, the resulting high energy plasma blows off in the coil direction to increase the thrust efficiency. To calculate the initial velocity distribution of the moderator plasma, we conducted simulations by using SPH (Smoothed Particle Hydrodynamics) method and the resulting ion velocities in the plasma are used as the input data for the 3D hybrid code. And then, we obtained an improvement of the thrust efficiency with the shaped target compared with the spherical target[8].

The plasma behavior in the magnetic nozzle is simulated and the estimation of the thrust efficiency for this shaped target and new coil configuration of case 2 is conducted. The results are shown in Fig. 7(a) (initial, Z-X plane) and Fig. 7(b) (t=11.08[μsec], Z-X plane). The resulting values for η and α are 71% and 0 %, respectively. If we use the initial distribution in case 2 calculated by the SPH method instead of the velocity distribution of isotropic expansion, the resulting values for η in case 2 is 64 %. So, the thrust efficiency of case 3 is grater than that of case 2 if the initial velocity distribution calculated by the SPH method is used.

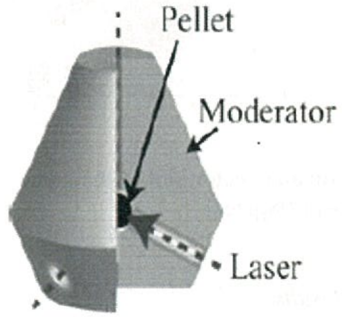
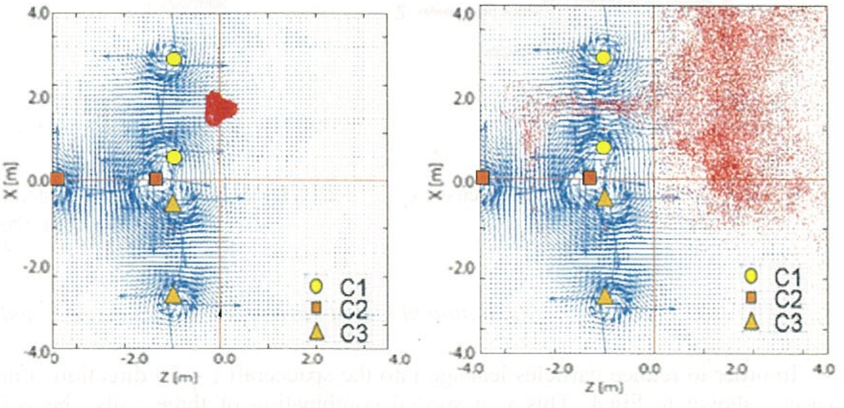


FIGURE 6. Shaped target (case3)



(a) (b)

FIGURE 7. Ion particle distribution and vector plot of magnetic field, (a) Initial, (b) t=11.08[micro sec]

CONCLUSION

In this paper, numerical simulations of plasma behavior in the magnetic nozzle are conducted by a three-dimensional (3D) hybrid code to estimate the thrust efficiency η. We also estimate a fraction (α) of plasma leaking in the forward (spacecraft) direction. In case1, two coils are arranged side by side and the magnetic nozzle is composed of two magnetic coils to increase the redundancy against the failure of the single coil. The thrust efficiency can be obtained as η=74%, but a part of the expanded plasma moved in the -Z direction across the center of the magnetic nozzle. In order to reduce particles leakage into the spacecraft (- Z) direction, new third coil is added and α value decreases to zero with η value of 73 %. To increase the thrust efficiency more than 80 %, the shaped target is proposed and used, and then the thrust efficiency can be obtained as η=71%. When the spherical moderator is used, the obtained thrust efficiency is less than that of case 3. This result of decrease in the thrust efficiency is consistent with the results in ref 8. On the other hands, the improvement of thrust efficiency in case 3 is still needed in the future.

In the laser fusion rocket, single solenoidal coil is normally used for the magnetic nozzle[3], while here we propose to use multiple (twin, triplet) coils for the NEP. The twin coil system would increase the redundancy against the failure of the single coil, resulting in the increase of system reliability, however the system mass will increase with increasing a number of coils and the forces exerted between the coils would be complex and difficult to estimate. These must be taken into consideration in designing the NEP system. Furthermore, we have to achieve the development of the injection techniques of a propellant pellet to the arbitrary position and the establishment of the steering techniques of laser beam to irradiate the propellant pellet when the propellant position is moved.

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