

Improvement of Thrust Efficiency of Laser Fusion Rocket with Shaped Target

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Abstract. This paper explains numerical analysis for a shaped target. The shaped target is made of fusion pellet and the pellet is surrounded by a moderator (propellant). The thrust efficiency can be improved by using the shaped target. We take up here typical models for the thrust efficiency improvement and for direction control. As a result of calculation, we have obtained an improvement of the thrust efficiency reaching 78 % with a shaped target, while it was only 66 % with a unshaped target. We also have obtained about 5 degrees of a steering angle.

1. Introduction

The laser fusion rocket (LFR) is an innovative idea proposed by Hyde^[1] and it is an important subject of research for future interplanetary mission since it could furnish both large specific impulse and power. A fusion reaction can release a large amount of energy and easily produce plasma of high temperature and density. The resulting plasma flow can be controlled by properly designed applied magnetic field configuration, i.e., a magnetic thrust chamber. In the laser fusion rocket, the chamber is composed of a solenoidal superconducting coil.

The fusion reaction occurs by irradiation of a laser onto a fuel pellet and the resulting plasma expands isotropically. The plasma is a good conductor, so when a magnetic field is applied, the plasma particles move around the magnetic field, i.e., Larmor motion starts. This circular motion induces diamagnetic currents, sweeping aside the field of the chamber. The compressed field, however, pushes against the plasma, and finally redirects the plasma to produce thrust (Fig.1). Thus the laser fusion rocket could realize a very high exhaust velocity of plasma as compared with existing systems. This fact makes the laser fusion rocket a promising candidate for interplanetary transport system.

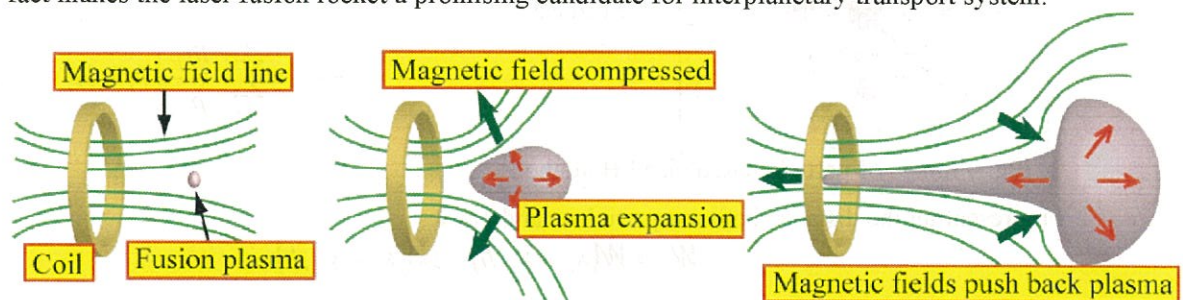


Fig. 1 Magnetic thrust chamber

One of the laser fusion rocket concept called VISTA (Vehicle for Interplanetary Space Transport Applications) was proposed by Orth *et al.*^[2] This vehicle uses deuterium-tritium fusion. Its specific impulse is 17,000 s with a thrust efficiency about 60% (Fig.2)

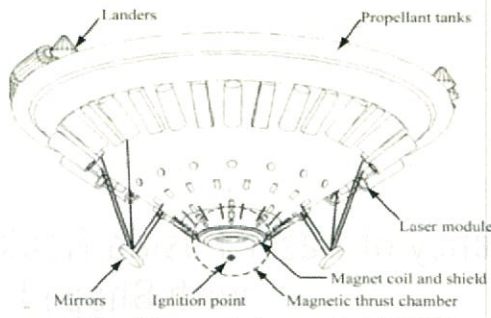


Fig. 2 Laser fusion rocket VISTA

A method of changing the magnetic configuration has been studied to improve the thrust efficiency of laser fusion rocket. Sakaguchi *et al.*^[3] use two coils, a rear coil is added to improve thrust efficiency, and they have obtained an improvement of thrust efficiency reaching 75%.

We here propose a method of achieving a higher thrust efficiency with a shaped target for the laser fusion rocket.

2. Shaped Target

The shaped target is made of fusion pellet and the pellet is surrounded by a moderator (propellant). Plasma generated by laser fusion in the pellet collides with the moderator to produce a large 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.

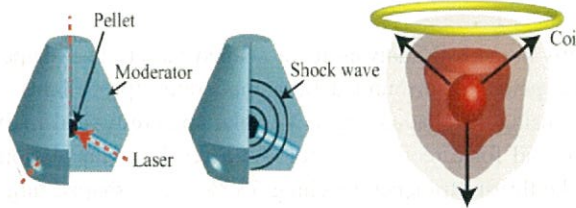


Fig. 3 Expansion process

SPH (Smoothed Particle Hydrodynamics) method^[4] is used as a computational tool for the collision process between the fusion plasma and the moderator. The resulting ion velocities in the plasma are the input data for a 3D hybrid code which treated ion as a particle and electron as fluid.

3. SPH Method

To use Lagrangian grid in SPH method has advantages in treating large deformation and boundaries in the very instant explosion process. In the SPH method, the fluid is represented by particles which are typically of fixed mass, and follow the fluid motion. The particles have fluid quantities such as mass m , velocity vector v , position vector x etc, and form the computational frame for the particle differential equations governing the conservation laws. In the standard SPH method, for a function f , the approximation of its function value at a certain location or particle i as well as its gradient can be expressed as summation interpolants over the neighbor particles using a smoothing kernel function W with the smoothing length h . In other words, the particle has the extension according to the leveling function in the SPH method. (Fig.3)

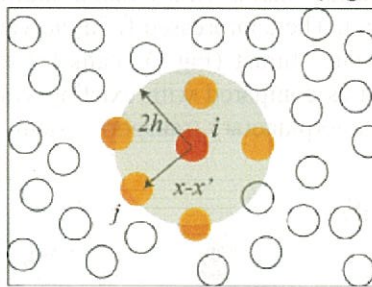


Fig. 4 Image of particle based on SPH method

h : smoothing length

x : position vector of the center of a particle

$$\langle f_i \rangle = \sum_{j=1}^N \left(\frac{m_j}{\rho_j} \right) f_j W_{ij} \quad (1)$$

$$\langle \nabla f_i \rangle = \sum_{j=1}^N \left(\frac{m_j}{\rho_j} \right) f_j \nabla_j W_{ij} \quad (2)$$

If representing the distance between particles i and j as r_{ij} ,

$$W_{ij} = W(x_i - x_j, h) = W(|x_i - x_j|, h) \quad (3)$$

$$\nabla_i W_{ij} = \frac{x_i - x_j}{r_{ij}} \frac{\partial W_{ij}}{\partial r_{ij}} = \frac{x_{ij}}{r_{ij}} \frac{\partial W_{ij}}{\partial r_{ij}} \quad (4)$$

The SPH method calculates the state of particles by using EOS interpolated by the above-mentioned concept.

4. Numerical Model and Result

4.1 Comparison between shaped moderator and unshaped moderator

We investigate here two kinds of moderator to improve the thrust efficiency; the moderator was shaped and unshaped. The thrust efficiency η is estimated by the following expression.

$$\eta = \frac{\sum m v_z (\text{Total Z direction momentum})}{\sum m |v_0| (\text{Total initial momentum})} \quad (5)$$

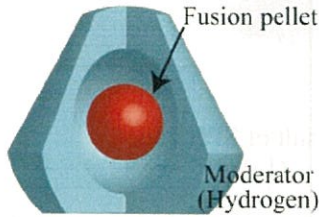


Fig. 5 Shaped moderator

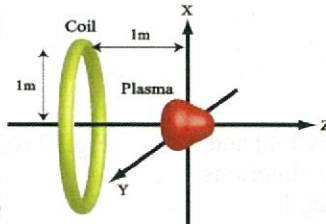


Fig. 6 Calculation model of 3D hybrid code

Table1 Computational condition

Pellet mass [mg]	0.141
Moderator mass [mg]	100
Pellet density [kg/m ³]	0.2696
Moderator density [kg/m ³]	3.411
Time step Δt [nsec.]	0.1
Number of particles	110000
Coil radius [m]	1.0
Coil current [A]	3.57×10^9
Coil position along Z [m]	-1.0
Plasma coordinate [m]	(0,0,0)
Plasma mass [mg]	100
Time step Δt [nsec.]	0.277
Number of particles	100000

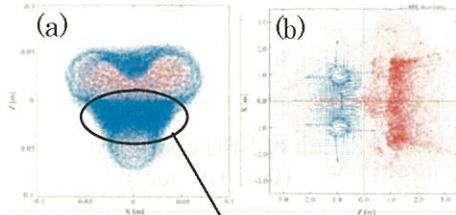


Fig. 7 Result of (a) SPH code (1.0×10^{-6} sec.), (b) 3D hybrid code (11.08×10^{-6} sec.)

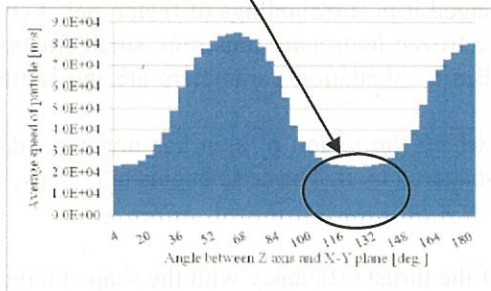


Fig. 8 Average speed of particle

Energetic particles from the fusion pellet are located at the center, and the 1cm-thick moderator (Hydrogen) is placed around the fusion pellet (Fig.5). The time step of SPH code is set to be 0.1×10^{-9} seconds, while the time step of 3D hybrid code is 0.277×10^{-9} seconds. (Table1)

As a result of calculation, the thrust efficiency was 78 % with the shaped moderator, while it was only 66 % when the moderator was not shaped, i.e., spherical moderator. An isotropic expansion in plasma is observed with the unshaped moderator. However, with the shaped moderator, plasma has started to blow off from the part where the moderator is thin (Fig.7). These particles with fast speed were deflected in a positive direction of Z-axis by strong magnetic field in the vicinity of the coil. Other particles were deflected in the same direction because its speeds are slow

(Fig.8). Therefore, the thrust efficiency is improved by shaping the moderator.

4.2 Application

The research of controlling traveling direction by changing configuration of the magnetic thrust chamber was done before [6]. We think that the shaped target can also be used for directional control by controlling direction of jet with the shaped moderator. A calculation model is given in Fig.9. α is an angle that inclines the target and β is an angle of the thrust vector, i.e. the steering angle. We have changed α to 0, 30, 60, 90, 120, 150 and 180 degrees. Also we cut a part of the moderator to lose the symmetry of the jet of plasma (Fig.10). We expect that the thrust vector with β (Steering) angle would be generated because the jet of plasma is asymmetrical. In this case, the calculation parameters are the same as in the above model.

Thrust efficiency and steering angle as functions of inclination angle is shown in Fig.11. When the inclination angle α was 120 degrees, it is found that the steering angle β was the largest value of 4.9 degrees, and the thrust efficiency was 65.8 %. The result of cut model in the SPH code is shown in Fig.12. It is found that the symmetrical blow off is lost. The steering angle obtained is 3.96 degrees, and the thrust efficiency was 66.8 % with the cut model.

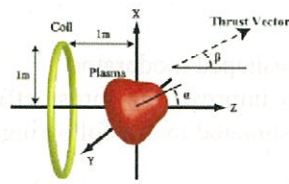


Fig.9 Calculation model

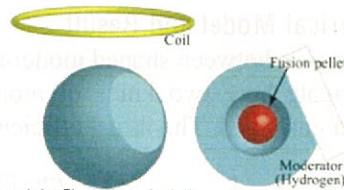


Fig.10 Cut model for direction control

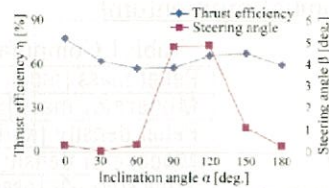


Fig.11 Thrust efficiency [%] and steering angle [deg.] as functions of inclination angle [deg.]

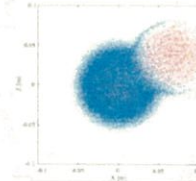


Fig.12 Result of SPH code (1.0×10^{-6} sec.)

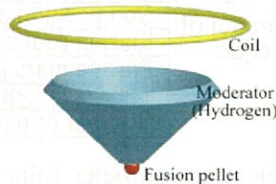


Fig.13 Cone model for radiation shielding

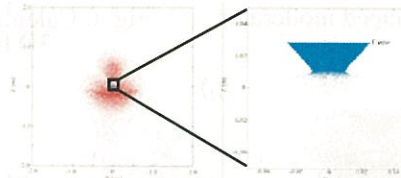


Fig.14 Result of SPH code (0.4×10^{-6} sec.)

4.3 Cone shape moderator

The frozen hydrogen would contribute to the radiation shielding of solenoidal superconducting coil [5]. So, we shaped the moderator to the cone and arranged it in surroundings of fusion pellet (Fig13). The fusion neutrons are absorbed and scattered by the frozen hydrogen, thus only small fraction of them will reach the solenoidal superconducting coil. Basic calculation parameters are the same as in the above model.

It is observed from Fig.14 that there is a part where the fusion plasma has not expanded. This is because the plasma collided with the cone and is scattered by it. The cone begins to collapse.

5. Conclusion

In this study, we have obtained an improvement of the thrust efficiency with the shaped target. We also found that the shaped target can be applied to a direction control. However, the thrust efficiency decreased with the direction control model. So, it is important to consider the tradeoff between the steering angle and the thrust efficiency.

In the cone model, it is necessary to treat light particles with fast speed from the fusion plasma and heavy particles with low speed from the cone at the same time. This fact makes numerical analysis difficult. The numerical study is now under way. This time, I only have described a present status of the study.

References

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