Parametric Design Study of Laser Fusion Rocket

Hideki NAKASHIMA*, Hidetoshi SHOYAMA*, Yukinori KANDA*
and Yasuyuki NAKAO**

Abstract

Fusion offers the potential for a very high specific power and a large specific impulse. Thus, fusion rocket is a leading candidate as a spacecraft for manned exploration of the solar systems.

We present here a parametric design study of the laser fusion rocket. The parameters varied include pellet gain (G=300~2000), fusion repetition rate (f=10~100Hz), and fusion fuel (DT, D^3He).

First, the mass contributed by each component of the rocket such as laser driver is evaluated, and then the masses are summed over the components to obtain the total mass which is further divided by fusion power to estimate the specific power. Using the specific power, flight performance is compared between the rocket designs. In the comparison, the figure of merit used is the minimum time required for travel of a fixed distance.

We found that there exists an optimal value for each design parameter which brings about the best flight performance of the rocket. However, the optimal values thus obtained are far above the values needed for terrestrial application, although some ambiguities may exist in the values due to the lack of the data base for the design parameters.

It is also found that the laser fusion rocket fueled with DT or D^3He has the potential advantages over other propulsion systems such as fission rocket for interplanetary travel.

1. Introduction

Fusion rockets have potential advantage over conventional rockets such as chemical ones. These advantages include (1)high characteristics exhaust velocity (or specific impulse), (2)high engine thrust-to-weight ratio, (3)high power level and (4)long mission life. These features make the fusion rockets potentially attractive for manned exploration of the solar systems. Bussard (Ref.1) proposed a fusion rocket based on magnetic confinement scheme and fueled with DD, whereas for inertial confinement fusion Orth et al.(Ref.2) proposed a spacecraft concept called VISTA which will be capable of manned Mars missions with a payload of 100 tons, and a total mission duration of roughly 100 days, including a stay on the planet of about 10 days.

Figure 1 shows the schematic layout of the fusion rocket which derives thrust from laser-induced fusion microexplosion. The mass and energy flows are given in Fig.2. Fusion pellets are injected into a magnetic thrust chamber. At the same moment, the laser is fired to induce the microexplosion in the pellets. The resulting fusion output is converted into thrust. Some of the fusion energy is picked up to power-supply the laser for next shot. The waste heat arising from inefficiencies in the driver and power systems is ejected by a heat pipe radiator.

In a previous paper (Ref.3), we discussed some design aspects of a rocket powered

---

* Department of Energy Conversion Engineering, Kyushu University,
Kasuga, Fukuoka 816, Japan

** Department of Nuclear Engineering, Kyushu University,
Hakozaki, Fukuoka 812, Japan

by the laser-induced fusion microexplosion.

We present here a parametric design study of the laser fusion rocket (Ref. 4). The parameters varied include pellet gain (G=300~2000), fusion repetition rate (f=10~100Hz), and fusion fuel (DT, DD and D^3He). In Sec. 2, the code system which carried out the parametric study is described. Sec. 3 is devoted to the results and discussions.

2. System Design

Figure 3 shows a flow-chart of the rocket design code developed and installed into a personal computer.

(i) The input parameters are the energy (E) of laser driver, the coil angle (θ), the repetition rate (f) of pellet microexplosion, etc.

(ii) According to the work of Rosen and Lindl (Ref. 5), a pellet gain (defined as the ratio of fusion energy to laser energy) is calculated for the DT pellet as a function of laser driver energy. The starting point is an assembled DT fuel configuration, i.e., one that is about to burn as shown in Fig. 4. A hot-DT igniter region (hot spark) of radius R_H is surrounded by nearly Fermi-degenerate (cold) DT fuel of radius R_C. The assembly is assumed to have internal energy ηE, where E is the original driver energy and η represents a coupling efficiency. Figure 4 also shows variation of ρ(density), P(pressure) and T(temperature) with R(radius) in the Meyer-Ter-Vehn(MTV) model (Ref. 6). The isobaric MTV model enforces a constant pressure throughout the assembled fuel.

The maximum pellet gain is given by

$$G_{max}=326.07\times(0.1\times E)^{0.3},$$

where η=10% and α(isentrope factor)=2 are assumed. E is in units of MJ. The results are shown in Fig. 5 where the effects of varying the R_H are also given.

We have an another option which could specify an arbitrary pellet gain for a specified laser driver energy (second option).

(iii) A two-dimensional collisionless particle-in-cell (PIC) code is written to analyze the interaction between plasma debris derived from the DT pellet microexplosion and magnetic field applied in the thrust chamber to estimate the thrust conversion efficiency.

R-Z geometry is used and the Maxwellian field equation is solved together with the equation of motion for the plasma particles (Ref. 7). The calculational geometry adopted is shown in Fig. 6. The thrust conversion efficiency (η_m) in terms of momentum is given in Fig. 7 as a function of θ (angle subtended from the central axis to the magnetic coil). The efficiency η_m is defined as

$$\eta_m=\frac{\Sigma m v_z}{\Sigma m|v_0|},$$

where m is the plasma particle mass, v_z the Z-component of its velocity, and v_0 the initial velocity. The sum(Σ) is carried out over the plasma particles. The coil has a radius of 13m, carries a current of 18MA, and stores six times the kinetic energy of the pellet. The efficiency has a broad maximum at θ~50°, and reaches ~66%. Using the least square fit, the efficiency is expressed as

$$\eta_m=-0.05726\theta^2+6.030\theta-91.79$$

The formula is incorporated into the design code. The details will be given elsewhere.

(iv) The mass contributed by each component of the rocket is evaluated according to Ref. 8, and for illustrative purposes, the results are summarized in Fig. 8 for an example case with E=5MJ and f=30Hz. Note that the radiator mass increases very sharply with increasing the pellet gain (it increases much faster than the pellet gain).

The masses are summed over the components to obtain the total mass which is then used to estimate a specific power $\eta_{PL}(=P/M_{PL})$, where P is the fusion power converted into thrust and M_{PL} is the power plant mass including a payload mass of 100 ton. P is given by

$$P=\alpha_P\times E\times G\times f\times\eta_m^2,$$

where α_p is the fraction carried by charged particles of the fusion output.

(v) Using the specific power η_{PL}, flight performance is compared between the rocket designs. In the comparison, the figure of merit(FOM) used is the minimum time (T_{min}) required for travel of a fixed distance(D). The T_{min} is given by (Ref.9)

$$T_{min}\sim\left(\frac{D^2}{\eta_{PL}}\right)^{\frac{1}{3}}$$

Thus, the rocket design characterized by a larger value of η_{PL} is preferable.

(vi) A schematic layout of the rocket design is drawn by a computer graphic software with the input data derived from the processes (i) to (v).

3. Results and Discussions

Figure 9 shows the specific power (η_{PL}) obtained as a function of G(pellet gain). The laser energy of 5MJ is assumed and the second option is adopted in the target design. The plant mass M_{PL} increases faster than the fusion output P with increasing the pellet gain G due to the increase in the mass of radiator for ejecting the increased waste heat (See Figure 8). Thus, there exists an optimal value for each design parameter which brings about the best flight performance of the rocket. However, the optimal values obtained (G=1000,f=50Hz) are far above the values needed for terrestrial application (where G=~100 and f=~10Hz), although some ambiguities may exist in the values due to the lack of the data base for the design parameters.

Table 1 compares the η_{PL} values among the various rocket designs. The pellet gains assumed are 250 for D^3He and DD pellets (Ref. 10), and 1500 for the DT pellet. For comparative purposes, the value for a fission-electric rocket is also given (Ref.11). In evaluating the η_{PL} values, the total fusion (or fission) output is used for P. It is found from this table that the laser fusion rocket fueled with DT or D^3He has the potential advantages over other propulsion systems such as fission rocket for interplanetary travel.

A particular fusion rocket design that could perform manned mission to Mars is now in progress.

Some studies relevant to the fusion rocket were also performed by our group. These include:

(i) numerical simulation for magnetically insulated inertial confinement fusion (MICF) pellet to examine the pellet gain reported by Kammash. (Ref.12) (Kammash and Galbraith proposed the application of the MICF pellet to space propulsion. (Ref. 13))

(ii) implosion simulation for DT igniter/D^3He fuel pellet to estimate the pellet gain(Ref.14)

(iii) plasma energy recovery by using a pick up coil system as applied to a D^3He inertial confinement fusion reactor(Ref.15)

(iv) analysis of plasma behavior in an applied magnetic field to estimate the Rayleigh-Taylor instability(Ref. 16).

We feel that a design of high gain pellet with a reasonable driver energy (E=1~10MJ) is essential for realizing the laser fusion rocket. The pellet gain G_{sys} required for the rocket system is given by

$$G_{sys}=\frac{1}{\alpha_p \times \eta \times \eta_{pick}},$$

where η_{pick} is the efficiency of pick up coil system for extracting the driver energy from the charged particle energies of the fusion output. For a typical example with α_p=0.25 for DT pellet, η=0.1 and η_{pick}=0.1, the G_{sys} required is as high as 400.

Examination of plasma instabilities such as Rayleigh-Taylor one is also necessary to ensure the feasibility of the magnetic nozzle concept adopted here in the thrust chamber design. (The plasma should not be diffused out across the magnetic field during its expansion due the instabilities.)

References

1. R.W.Bussard, J. Propulsion 6,(1990) 567
2. C.D.Orth, et al., "The VISTA Spacecraft-Advantages of ICF for Interplanetary Fusion Propulsion Applications,"UCRL-96676(1987)
3. H.Nakashima, et al., Proc. 16th Int. Symp. Space Technology and Science, p.113, Sapporo 1988.
4. H.Nakashima, et al., "Design Study of Laser Fusion Rocket"(in Japanese), Kakuyugo Kenkyu 66,(1991) 291
5. M.D.Rosen, J.D.Lindl, Laser Program Annual Rep. UCRL-50021-83(1984)3-5
6. J.Meyer-Ter-Vehn, Nucl. Fusion 22,(1982) 561
7. D.O.Dickman, et al., Phys. Fluids 12,(1969)1708
8. R.A.Hyde, et al., AIAA Paper No.72-1063(1972)
9. R.A.Hyde, "A Laser Fusion Rocket for Interplanetary Propulsion,"UCRL-88857(1983)
10. C.D.Orth, Proc. Special Minicourse on Fusion Application in Space (1988) p.113
11. J.R.Roth, Fusion Technol. 15,(1989)1375
12. H.Nakashima, et al., Submitted to Nucl.Fusion
13. T.Kammash and D.L.Galbraith, Nucl. Fusion 29(1989)1079
14. H.Nakashima, et al., Presented at Japan-US Seminar on Physics of High Power Laser Matter Interactions, Heian-Kaikan, Kyoto, March 9-13,1992
15. H.Nakashima, et al., To be published in Fusion Engineering and Design
16. H.Nakashima, et al., To be published in Fusion Technology

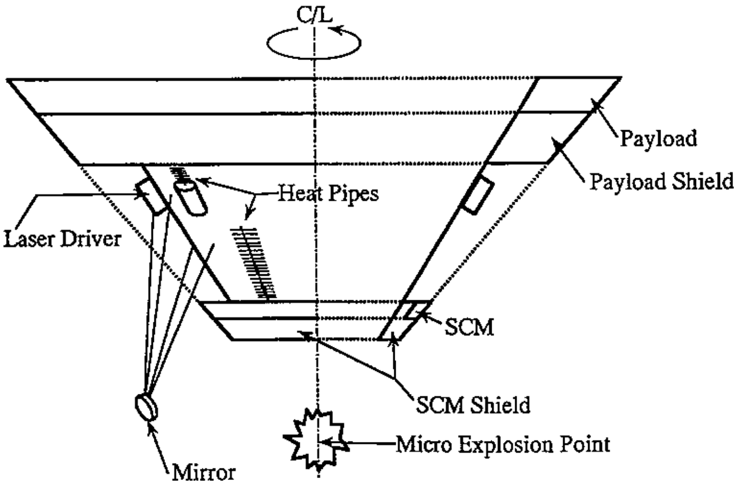

Fig.1 Schematic layout of laser fusion rocket

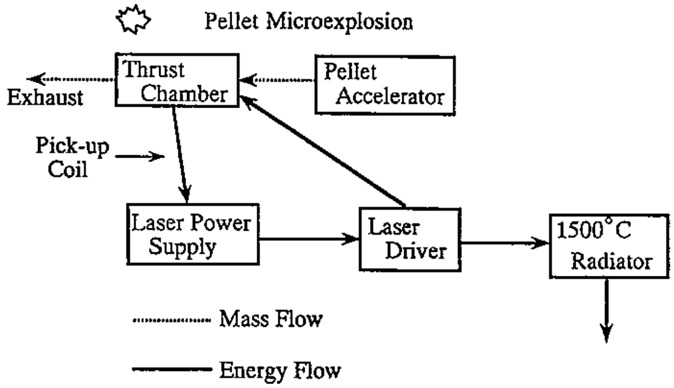

Fig.2 Mass and energy flow diagram in laser fusion rocket

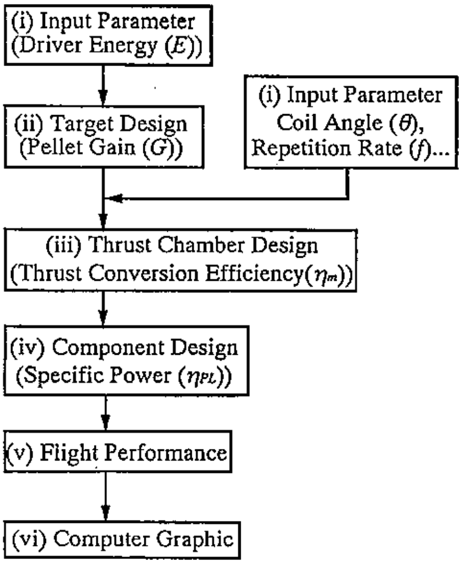

Fig.3 Flow chart of design code system

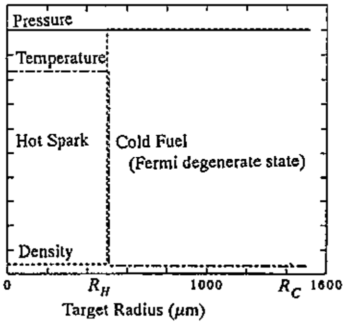

Fig.4 Final configuration of DT pellet after implosion (MTV model)

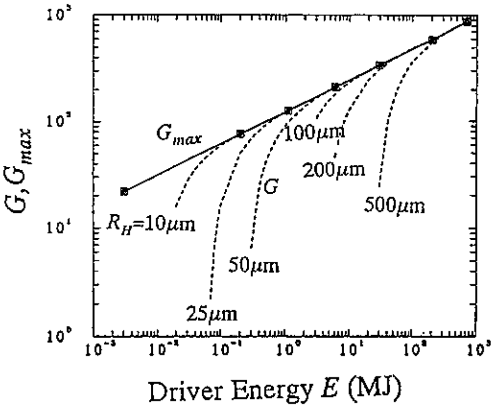

Fig.5 Pellet gain versus laser energy (η=0.1,α=2)

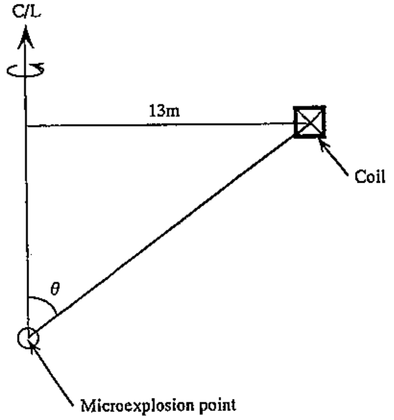

Fig.6 Calculational model for estimating the thrust conversion efficiency (R-Z geometry)

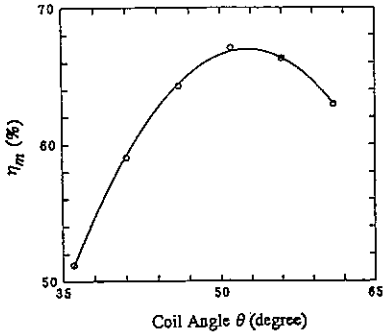

Fig.7 Thrust conversion efficiency (momentum) versus θ at 1μs after explosion

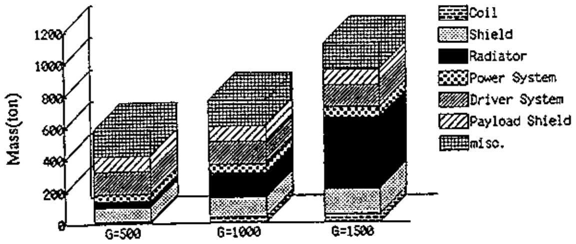

Fig.8 Summary of component mass

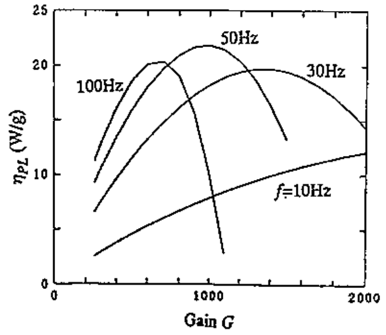

Fig.9 Specific power versus pellet gain

Table 1 Comparison of specific power

	DT	DD	D^{3}He	fission-electric
η_{PL} (W/g)	19.4	14.5	20.8	———
η_{PL}^* (W/g)	200.5	———	———	2.0

$$\eta_{PL}^*=\frac{P^*}{M_{PL}}$$

P^* = fusion (fission) power