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A NOVEL FUSION SCHEME FOR SPACE PROPULSION

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Abstract

A recently proposed approach to fusion power is examined for applicability to space propulsion. This promising new scheme combines the favorable aspects of magnetic and inertial fusions in that physical confinement of the hot plasma is provided by a metallic shell, while thermal insulation is provided by a strong, self-generated, magnetic field. In contrast to conventional inertial confinement, the plasma in this approach is created on the inside of a shell as a result of a laser beam impinging through a hole and striking the inner wall which is coated with a fusion fuel such as deuterium-tritium. Since no pusher is employed in this scheme the laser-plasma coupling is significantly better than implosion type inertial fusion, and as a result very attractive energy multiplications can be generated. Because of these unique properties and relative simplicity of the system, it is shown that it is particularly suitable for space propulsion since it can generate thrusts in the tens of kilonewtrons and specific impulses of several thousands of seconds.

I. Introduction

Almost all of the exotic propulsion schemes that have been proposed for space explorations of the next century can be characterized as high thrust or high specific impulse but rarely both. It has been argued, for example,[1] that missions that are tailored to electric propulsion capabilities would have a relatively large total impulse requirement which could be supplied over relatively long periods of time (such as in deep space missions or for maintaining orbits of large satellites in earth orbit). Mission requirements for very large accelerations (thrust) and only modest total impulse are perhaps not well suited to electric propulsion because the mass of the power source could be comparable to the mass of the chemical propellant saved and possibly far more expensive. Chemical propulsion, on the other hand, may provide large thrust but is generally limited to modest specific impulses (<500 sec) which renders it questionable for some of the objectives cited above.

In this paper we discuss a scheme which could provide significantly large specific impulses as well as very sizable thrust. It is based on a new inertial confinement fusion scheme that has generated a great deal of interest for potential earth-based power reactors and which, as will be shown later, has unusual potential for space applications. It is called the "Magnetically Insulated Inertial Confinement Fusion" (MICF) reactor recently proposed by Hasegawa et al.[2] This approach combines the favorable aspects of magnetic and inertial confinement fusions in that physical confinement of the hot plasma is provided by a metallic shell, while thermal insulation is provided by a very large, instantaneous, self-generated magnetic field. The underlying principle of MICF is the generation of a fusion grade plasma inside a spherical shell by means of a laser (or particle) beam that enters the shell through a hole at the top as illustrated in Fig. 1. When such

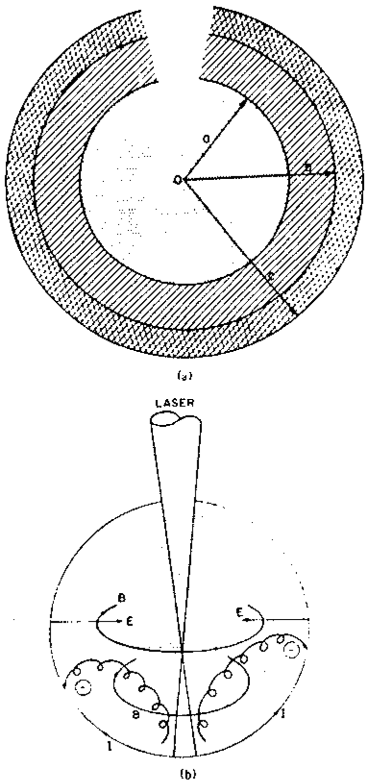

FIG. 1. Schematic diagram of (a) the reactor chamber and (b) process of magnetic field generation.

a beam strikes the inner surface of the shell which is coated with fusion fuel (e.g., Deuterium-Tritium, DT) a fusion plasma is formed at the core at nearly solid state density. If such a plasma is simultaneously heated by the laser to thermonuclear temperatures such as 10 keV, then it can undergo fusion reactions giving rise to large energy releases.

In the case of deuterium-tritium fuel, the reaction of interest is

$$D + T \rightarrow {}_2He^4 + n + 17.6 \text{ MeV} \tag{1}$$

where the alpha particle (${}_2He^4$), born at 3.5 MeV energy, is expected to maintain the temperature necessary for the continuation of the fusion reactions in the plasma. Because of the very strong, self-generated magnetic field, the heat transport from the plasma to the surrounding shell is drastically inhibited and, as a result, the plasma will continue to burn and expand until the whole pellet is vaporized. If at that point the plasma (which now consists of the DT ions, the metallic ions, and electrons) is allowed to expand into an expansion chamber and then exhaust through a nozzle we find that specific impulses well exceeding 1000 secs, and thrusts in the tens of kilonewtons can be generated. If used as a power source it will be shown that such a system can also generate hundreds of megawatts of electric power, which if need be, can be used as a power source for an electric propulsion scheme such as the magnetoplasmadynamic (MPD) thruster.[3]

In the remainder of this paper we will present the basic equations that characterize the dynamics of the system, and propose in a cursory fashion a conceptual design that might address the desired space applications.

II. Equations and Analysis

We begin by assuming that a laser-illuminated plasma with the appropriate properties is formed at the center of the shell and that a sufficiently strong magnetic field is simultaneously generated to inhibit the particle and energy diffusion from the expanding core. For simplicity we shall also assume that a time-dependent, zero dimensional analysis is adequate to describe the dynamics of MICF. We treat the plasma as having three thermalized species: fuel ions, electrons, and alpha particles plus an arbitrary number of fast alpha energy groups. If we further treat each thermal species as an ideal gas then it can be shown from the second law of thermodynamics that, with dq as the energy supplied to the gas from the outside, the time rate of change of the thermal energy of an expanding gas is given by[4]

$$\frac{1}{(\gamma-1)} \frac{d}{dt}\left\{\frac{4}{3}\pi r^3 nT\right\} + 4\pi r^2 nT \frac{dr}{dt} = \frac{dq}{dt} \tag{2}$$

where γ is the ratio of specific heats, n is the gas density, T is its temperature and r is its radius. The dynamics of each component of the plasma will be described by a particle and an energy balance equation. Thus for the fuel ions we can write[4]

$$\frac{d}{dt}\left\{\frac{4}{3}\pi r^3 \frac{n_f T_f}{\gamma-1}\right\} = \frac{4}{3}\pi r^3 \left\{S_n - \frac{1}{2} n_f^2 \langle\sigma v\rangle_f\right\} \tag{3}$$

$$\frac{d}{dt}\left\{\frac{4}{3}\pi r^3 \frac{n_f T_f}{\gamma-1}\right\} + 4\pi r^2 u n_f T_f = \frac{4}{3}\pi r^3 \Bigg\{ \frac{3}{2}\frac{n_f n_e}{(n\tau)_{ef}}(T_e - T_f) + \frac{3}{2}\frac{n_f n_\alpha}{(n\tau)_{\alpha f}}(T_\alpha - T_f) + S_n E_s - \frac{1}{2} n_f^2 \langle\sigma v\rangle_f \left(\frac{3}{2} T_f\right) + \sum_j \left(\frac{dE_j}{dt}\right)_f \Bigg\} \tag{4}$$

In these equations n_f is the fuel ion density, T_f the fuel ion temperature; n_e is the electron density, T_e the electron temperature; n_α the thermalized alpha density and T_α is the corresponding alpha temperature. The radius of the plasma, r, is assumed not to exceed the inside radius of the solid fuel, and $u = dr/dt$. The quantity S_n represents the source strength per unit volume of refuelling as a result of evaporation of solid fuel, and E_s is the average energy carried by each of these source fuel ions. Since the fuel ions exchange energy with the electrons and the thermalized alphas, such exchanges are represented by $(n\tau)_{ef}$ and $(n\tau)_{e\alpha}$ in Eq. 4, while fusion energy production rate in the same equation is given by $\langle\sigma v\rangle_f$ with σ being the fusion reaction cross section. The last term in Eq. 4 represents the rate which the j_{th} group of fast alphas gives up energy to the fuel ions and these terms are summed over all the fast alpha groups.
Similar equations can be written for the electrons of the plasma and the thermal alphas but in the interest of brevity we shall not reproduce them here, and urge the reader to consult Ref. 4 for these details and those associated with the fast alpha species. For the fueling rate we have assumed that for every bremsstrahlung photon emitted by the hot plasma electrons that strikes the solid fuel wall, an electron with an energy equal to that of the incident photon will emerge, along with an ion at roughly zero

energy, and both will join the hot plasma at the core. For that reason no radiative loss term was included in the electron energy balance equation of this analysis.

In order to obtain the solution of the desired equations one must obtain the energy exchange characteristic times $(n\tau)_{ij}$ available in Ref. 5, and the plasma expansion rate u, which is given by[2]

$$u = \frac{dr}{dt} = \beta \left[\frac{p - p_s}{\rho_s} \right]^{1/2} \qquad (5)$$

where

$$p = n_f T_f + n_e T_e + n_\alpha T_\alpha + \frac{2}{3} \sum_j n_j E_j \qquad (6)$$

and ρ_s is the density of the metallic shell, p_s is the pressure in that shell, and β is a parameter determined from simulation and experiment. A typical value of this parameter is $\beta \approx 0.1$ which along with an initial density of $10^{21} cm^{-3}$, an initial ion and electron temperature of 10 keV, and an initial plasma radius of 0.25 cam were utilized in producing some of the results to be discussed below.

III. Energy Multiplication Due to Fusion

The most important parameter that characterizes the effectiveness of the fusion system is the energy multiplication factor Q. If we assume a perfect coupling between the laser radiation and a plasma with the above density and temperature, then an input energy of about 300 kilojoules is required. CO_2 lasers, which are known to be the most efficient of lasers, are technologically within reach of such energy, although in reality a much higher energy (perhaps about a megajoule) may be required in order to create the plasma by ablation of the solid fuel, and then heating it to the desired temperature. If we allow the plasma to burn for a time of 2 μsecs then the variation of Q with the initial plasma density, and its variation with the initial radius are given in Tables 1 and 2 respectively.

Table 1

$N_o (cm^{-3})$	Q
8.0×10^{20}	38.79
1.0×10^{21}	59.18
2.0×10^{21}	132.00
4.0×10^{21}	210.11
1×10^{22}	361.75

Table 2

r_o (cm)	Q
0.15	14.29
0.25	59.18
0.30	75.86
0.35	88.84
0.40	99.32

As an example if we choose the conservative case typified by $N_o = 10^{21} cm^{-3}$, $T_o = 10$ keV, $r_o = 0.25$ cm and $\beta = 0.1$ as a reference case then we find that Q = 59.18 after a burn time of 2×10^{-6} secs. If on the other hand, we let the plasma burn until r = 1.0 cm we find that a Q value of about 132 obtains with a time of only 9.3 μsecs. For the reference case we find that the net energy production is about 18.3 megajoules and if a repetition rate of 10 is used then this system will generate 183 megawatts of thermal power. Such a repetition rate has been suggested in several reactor designs,[6] and for the design suggested below this repetition time is compatible with the plasma escape time.

IV. MICF As a Propulsion Device

For the reference case alluded to above the calculation shows that the plasma radius would be 0.5 cm, the density $10^{21} cm^{-3}$, the mean plasma energy 30 keV, and Q is about 60 at the end of 2 μsecs. If we assume that the pellet at that instant is vaporized and both the DT plasma and that of the shell reach thermal equilibrium at a mean energy of 30 keV, then by energizing at that point a mirror-type magnetic field the charged particles will be trapped within the expansion chamber illustrated in Fig. 2. For the above parameters the plasma escape time through the nozzle is about 10^{-3} secs and the escape velocity of the DT ions is about 20 kilometers per second which translates to a specific impulse of about 2000 seconds. If the metallic shell happens to be tungsten then the escape velocity of these ions is roughly 1/4 that of the DT ions. For an initial tungsten shell of 0.002 cm thickness the thrust generated by the tungsten ions only upon exhaust is about 20 kilonewtons. Since the escape time ($\sim 10^{-3}$ sec) is much longer than the burntime (~2 μsec) a repetition rate of 10 is readily attainable, though conservative, and the system will operate almost at steady state. If we wish to exhaust the plasma through the magnetic mirror at the one nozzle we can tailor the magnetic field so as to minimize the escape through the other mirror. It should be noted however that both the specific impulse and the thrust will increase significantly if we allowed the pellet to expand until its radius reached a value of $r = 1$ cm. We recall that at that point Q reaches a value of about 132 and hence both the exhaust velocities and the escape time will change accordingly.

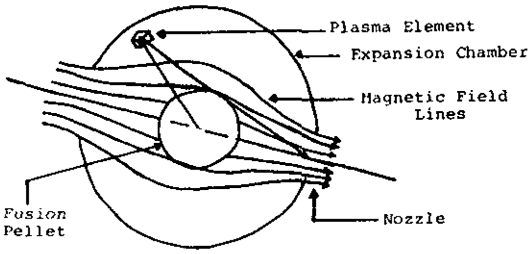

Fig. 2 Schematic of MICF Propulsion

We have shown that as a reactor operating on the basis of the reference case MICF produces 183 megawatts of thermal power through the neutrons generated by the DT reaction (See Eq. 1). At a thermal efficiency of 40% the electric power generated by the system is about 75 megawatts which would make it very attractive as a multimegawatt power source for an electric propulsion scheme such as MPD. That of course would necessitate using radiators to get rid of the waste heat and in that regard MICF is no different than any other Nuclear Electric propulsion scheme.

The neutron problem can be almost totally circumvented if another fusion fuel cycle (such as D-He^3) is used. In this case the reaction products will be primarily charged particles and as half of them escape through the left mirror of Fig. 2 their energy can be directly converted to electricity at very high efficiency (80-90%). The performance for such a thruster will be quite different however since, among other things, the temperature requirement is significantly higher than that of the DT fuel cycle. This aspect of it will be the subject of a future paper.

Returning to the reference case it is of interest to examine other properties that render MICF as an attractive propulsion system. Two very revealing parameters are the ratio (α) of the weight of the power plant to the thermal power produced, and the ratio of the power plant mass to the jet power generated by the thruster often referred to as the specific mass α_{TS}. It is known that the weight of the CO_2 laser per joule of energy is 9 kg/joule and for the reference case a laser delivering one half of a megajoule will weigh about 4.5×10^6 kg. With a power production of about 180 MW we see that α (thermal) $\cong$ 0.01. Moreover, since the jet power produced by MICF as a thruster is about 58 MW, then the specific mass is $\alpha_{TS} =$ 0.07, a very attractive value indeed.

In terms of a particular mission capability it is interesting to compare MICF with, say, perfect electric propulsion schemes for which the input power P_{in} is equal to the jet power P_J. Using an expression that can readily be deduced from standard rocket equation, we examine the case of an orbit transfer of a vehicle from low earth orbit (LEO) to geosynchronous earth orbit (GEO) for which the velocity increment is $\Delta V = 6000$ m/sec.[7] Choosing the initial mass of the vehicle to be 35,000 kg we find, for an electric propulsion system with a specific impulse $I_{sp} = 1000$, an input power of about 1.20 MW will be required to carry out the transfer in 10 days. At the same I_{sp} the MICF thruster with a power of 58 MW will achieve the same mission in about 5 hours.

It should be kept in mind that the above impressive results that can be generated by MICF propulsion are based on the reference case which represents a very conservative assessment of this scheme ($Q \sim 60$ at a burn time of 2 μsec). We recall that if we allow the fusion burn to last 9.3 μsec then Q would be about 132 and thus will have a profound impact on all the propulsion parameters such as I_{SP} and jet power. In fact we see from Tables 1 and 2 that we could significantly enhance its performance by merely changing the size of the pellet and/or the density of the initial fusion plasma.

V. Conclusion

We have examined in this paper the applicability of a new fusion approach to propulsion for space explorations of the next century. The Magnetically Insulated Inertial Confinement Fusion (MICF) appears to be especially suited for missions where large thrust as well as large specific impulse may be required. Because of the high power density of fusion fuels ($\sim 10^{15}$ joules/kg) such a thruster can generate on the basis of a conservative design thrust in the tens of kilonewtons and specific impulses of few thousand seconds. The preliminary calculations presented in this paper also reveal that significant enhancement in the performance of this system can be achieved with modest modifications of certain parameters that are, or shortly will be, within reach of technology.

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