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Fusion-Fission Hybrid Revisited – Potential for Space Applications

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In several recent papers, we addressed the case of fusion propulsion by focusing on the gasdynamic mirror (GDM) as a magnetic device in which fusion plasmas are heated to ignition by the reaction products resulting from the "at rest" annihilation of antiprotons in U^{238} targets. Unlike terrestrial fusion power systems where large *Q* (ratio of fusion power to injected power) values are required, only modest *Q*-values were shown to be adequate for space applications. In this paper, we focus on a bi-modal fusion propulsion system in which *Q*-values of about unity or less are needed since the GDM will serve mainly as a neutron source. It is well known that fusion reactions are neutron rich but energy poor, while fission reactions are energy rich but neutron poor. We make use of this fact by considering a system in which the GDM device serves as a fast neutron source surrounded by a blanket of Th^{232}, which we utilize to breed U^{233} and simultaneously burn it to produce energy. For a reasonable size blanket and a D-T plasma density, size and temperature, we find that the proposed hybrid system is capable of producing tens of gigawatts of thermal power per centimeter. If we use this power to heat a hydrogen propellant, we find that a seven meter long engine can generate a specific impulse of about 59,000 seconds at a thrust of about 8 mega-newtons at a propellant flow rate of about 130 kg/sec. Such a propulsion capability would allow many meaningful space missions to be carried out in relatively short times. Furthermore, such a hybrid system can generate large amounts of electric power for surface power applications once destination is reached.

Nomenclature

c_p	=	constant pressure specific heat
D	=	diffusion coefficient
F	=	thrust
g	=	earth's gravitational acceleration
Isp	=	specific impulse
L	=	plasma length
$\dot{m}$	=	propellant flow rate
m_f	=	dry mass of vehicle
N^{32}	=	density of thorium-232
N^{33}	=	density of uranium-233
n	=	number of neutrons produced per unit volume per unit time
n_p	=	plasma density
P_l	=	power deposited per unit length
P_r	=	power deposited per unit volume

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R_M	=	plasma mirror ratio
r_p	=	plasma radius
S	=	neutron source term
T	=	temperature
u	=	coolant flow velocity
v_{th}	=	ion thermal velocity
z	=	axial coordinate
ν	=	number of neutrons produced per fission
φ	=	neutron flux from fusion plasma
ρ	=	density
Σ_{at}	=	total thorium-232 and uranium-233 macroscopic absorption cross section
Σ_f	=	uranium-233 macroscopic fast neutron fission cross section
σ_f	=	fast neutron fission cross section
σ_γ	=	thorium microscopic capture cross section
$\langle \sigma v \rangle$	=	Maxwellian averaged fusion reaction cross section
τ	=	confinement time
τ_{RT}	=	round trip time

I. Introduction

THE use of fusion energy to propel vehicles in space has been investigated for several decades. Much of the earlier work[1-3] focused on inertial fusion where laser beams are employed to ignite target pellets containing fusion fuel to produce the needed energy. With the realization that laser systems are massive and complicated, other drivers were examined to see if they can deliver the required energy to the target at much lower mass. Here, the use of antimatter was found to be especially effective. Modest amounts of antiprotons are found to be adequate to trigger fusion propulsion,[4,5] but the engineering challenges associated with this approach[6] have to be addressed vigorously in order for it to be realizable. The major issue associated with the use of antimatter is availability since the current annual worldwide production rate stands at nanograms[7] while most fusion propulsion schemes appear to require quantities on the order of several micrograms. With the world effort in achieving fusion power for terrestrial use focused on toroidal devices, such as tokamaks, very little attention was paid to magnetic fusion for propulsion applications. These devices do not appear to lend themselves geometrically for exhausting energetic plasma particles to generate thrust. Open-ended magnetic devices, on the other hand, are found to be especially suitable because they can confine a plasma long enough to be heated before being ejected from one of the mirror ends to produce thrust. Of particular advantage in this regard is the gasdynamic mirror[8] (GDM) whose confinement properties are based on plasmas of such density and temperature as to make the ion-ion collision mean free path much shorter than the length. Under these conditions, the plasma behaves much like a fluid, and its escape from the system is analogous to the flow of a gas from a vessel with a hole. We focus on the GDM as the fusion component of the system we propose in this paper and demonstrate its usefulness for both space power and propulsion applications.

II. Concept Description and Analysis

The proposed system consists of a fusion component (GDM) in which deuterium-tritium (DT) plasma is confined and heated to such temperature as to produce the desired flux of fast (14.1 MeV) neutrons. The GDM is chosen to have a large aspect ratio, i.e. $L/r_p >> 1$, where L is the length and r_p the plasma radius, in order to insure stability against magnetohydrodynamic (MHD) modes. For such a geometry, it is expected that the neutrons will flow, on the average, radially into a blanket of radius R that surrounds the plasma. The blanket material is chosen to be thorium-232 (Th^{232}) whose atoms will undergo radiative capture reactions with the incident neutrons to form uranium-233 (U^{233}). This takes place in accordance with the scheme:

$$\mathrm{Th}^{232}(\mathrm{n},\gamma)\mathrm{Th}^{233} \xrightarrow{\beta^-,\,22\,\mathrm{m}} \mathrm{Pa}^{233} \xrightarrow{\beta^-,\,27.4\,\mathrm{d}} \mathrm{U}^{233} \tag{1}$$

where it is seen that the beta decay of the intermediate isotopes takes approximately 28 days before U^{233} begins to appear. This is especially important when addressing the steady state operation of the system, and how it may be reached. Not only will the incident fast neutrons lead to the breeding of U^{233} in this blanket, but they will also induce fission in this isotope to produce energy. Since the fusion component, namely the GDM, is called upon primarily to produce neutrons, it is important that the confinement characteristics of the device satisfy at most the break-even condition where the injected power is about equal to the fusion power. Such confinement can be expressed by[9]

$$n_p \tau = \frac{n_p R_M L}{v_{th}} \tag{2}$$

where n_p is the plasma density, τ is the confinement time, R_M the plasma mirror ratio, L the length and v_{th} the ion thermal velocity. If $n_p \tau$ is set equal to the Lawson's breakeven condition for DT plasma at 10 keV, namely ~10^{14} sec/cm^3, then for certain plasma density and mirror ratio, the above equation yields the required plasma length. For example, with an $n_p = 10^{16}$ cm^{-3}, $R_M = 55$, and $L = 7$ m, the Lawson condition is nearly satisfied. If $n_p \tau$ is reduced while the other parameters remain the same, then a larger injection power is required to sustain the neutron production. Assuming a 50%-50% DT mixture, the number of neutrons produced per cm^3 per second, n, is given by

$$n = \frac{n_p^2}{4} \langle \sigma v \rangle \tag{3}$$

where $\langle \sigma v \rangle$ is the Maxwellian averaged fusion reaction cross section. For $n_p = 10^{16}$ cm^{-3} at a temperature of 10 keV, $\langle \sigma v \rangle = 1.1 \times 10^{-16}$ cm^3/sec, and Eq. (3) yields $n = 0.25 \times 10^{16}$ cm^{-3}sec^{-1}. As these neutrons enter the blanket, they will interact with the thorium atoms to produce U^{233} and also interact with the uranium atoms to cause fission. These processes are represented by the following equations:

$$\frac{dN^{33}}{dt} = \varphi \sigma_\gamma N^{32} - \varphi \sigma_f N^{33} = 0 \tag{4}$$

$$\frac{dn}{dt} = D \nabla^2 \varphi - \Sigma_{at} \varphi + \nu \Sigma_f \varphi + S = 0 \tag{5}$$

Equation (4) gives the steady state production of U^{233} atoms as represented by the density, N^{33}, where φ is the neutron flux emerging from the fusion plasma. N^{32} is the Th^{232} density in the blanket, and σ_γ and σ_f are respectively the thorium microscopic capture cross section and the fast neutron fission cross section. In a steady state operating system, the neutron flux is obtained from the diffusion equation, Eq. (5), where D denotes the diffusion coefficient, Σ_{at} the total (Th^{232} and U^{233}) macroscopic absorption cross section, and Σ_f the U^{233} macroscopic fast neutron fission cross section. The quantity ν represents the number of neutrons produced per fission (~2.5), and S is the neutron source given by Eq. (3). Equation (4) reveals that in steady state, the density of bred U^{233} is related to the density of Th^{232} by the ratio of σ_γ / σ_f. Since the incident neutrons can also induce fission in thorium, as well as (n,xn; x >= 2) reactions, realistic values of σ_γ / σ_f should reflect integrals over the spectral distribution of neutrons. An MCNP (Monte Carlo Neutron Photon) simulation has shown that the spectral average value of σ_γ / σ_f is about 0.10, thus revealing that in steady state, the density of U^{233} remains as 1/10 that of Th^{232}. Solution to Eq. (5) using the boundary conditions of finite flux at the origin and vanishing flux at the outer boundary of the blanket has been shown[10] to have the form of the ordinary Bessel function of zero order, i.e. $J_0(r)$. When combined with N^{33} obtained from Eq. (4), and using 200 MeV as the energy produced per fission, the thermal power per unit length, P_l, produced by the system can be readily calculated. For a plasma of 5 cm radius and a blanket of 100 cm radius, along with the neutron source given by Eq. (3), it is shown that the system will produce

$P_l = 54\,\text{GW/cm}$ when no coolant ducts are included in the analysis. If such ducts are assumed to occupy 30% of the blanket cross section, then the thermal power will be reduced accordingly.

To assess the propulsive capability of the system, we begin with the familiar heat conduction equation which we employ to calculate the axial temperature profile in the coolant as it traverses the length of the blanket. The equation of interest is

$$\rho c_p u \frac{dT}{dz} = P_r \tag{6}$$

where P_r is the power deposited in the coolant per unit volume, T the temperature, u the flow velocity, ρ the density, and c_p the specific heat. Assuming all the parameters to remain constant, the above equation can be integrated to yield

$$T = T_0 + \frac{P_r}{\rho c_p u} z \tag{7}$$

with T_0 denoting the inlet temperature. Eq. (7) can be expressed in the form

$$T = T_0 + \frac{P_l}{\dot{m} c_p} z \tag{8}$$

with P_l being the power per unit length alluded to earlier, and $\dot{m}$ the propellant flow rate which we take to be 130 kg/sec. Recalling that the blanket length is taken to be the same as the plasma length, i.e. L = 7m, and using hydrogen as the propellant that enters at $T_0 = 0$, we find that the exit temperature corresponds to $T_{ex} = 1.21\,\text{keV}$. Clearly, the hydrogen will be fully ionized, and the exiting protons will have a velocity that corresponds to a specific impulse of Isp = 59×10^3 seconds. The corresponding thrust, F, is found to be 8 mega-newtons. Such propulsive capability would allow a rocket based on this system to reach destination in the solar system and beyond in relatively short times.

As an example, we consider a round trip journey to Mars assuming constant thrust, continuous burn, acceleration/deceleration type of trajectory for which the round trip time is given by[11]

$$\tau_{RT} = \frac{4D}{g\,\text{Isp}} + 4\sqrt{\frac{D m_f}{F}} \tag{9}$$

where D is the one-way linear distance between the points of travel, g the earth's gravitational acceleration, and m_f is the final (dry) mass of the vehicle. With D = 0.52 AU (0.78×10^{11} m) for Mars and a vehicle with 10^4 mT dry mass, Eq. (9) shows that such a round trip can be accomplished in about 21 days.

III. Conclusion

We have presented in this paper a propulsion system based on the fusion-fission hybrid in which fission reactions are triggered by fast neutrons generated by a DT plasma in a fusion component operating at or near breakeven condition. The fissile material, namely U^{233}, is bred in a thorium blanket that surrounds the plasma. In a steady state operation of the system, it is found that it is "subcritical" and capable of producing a specific impulse and a thrust that allows a ten thousand metric ton vehicle to make a round trip to Mars in about 3 weeks. Moreover, this seven meter reactor, when coupled to a thermal converter operating at about 40% efficiency, will produce approximately ten terawatts of electric power using its own generated fuel. Such large amounts of power can be of special significance in meeting the surface power needs once destination is reached.

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