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High-Thrust–High-Specific Impulse Gasdynamic Fusion Propulsion System

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The gasdynamic fusion propulsion system utilizes a simple mirror magnetic geometry in which a high-density plasma is confined long enough to generate fusion energy while ejecting charged particles through one end to generate thrust. At high densities the collision mean free path becomes much shorter than the length, making the plasma behave much like a continuous medium, a fluid. Under these conditions the escape of the plasma is analogous to the flow of a gas into a vacuum from a vessel with a hole. With the mirror serving as a magnetic nozzle the plasma-charged particles are ejected at very high energies, giving rise to specific impulses of well over 200,000 s, but at modest thrusts because of the smallness of their mass. We examine methods by which the thrust of this engine can be enhanced. On the one hand we explore the use of a hydrogen propellant that is heated by the radiation emanating from the plasma, which, upon exhausting through a nozzle, generates the additional thrust. On the other hand we focus purely on changing the properties of the injected plasma to achieve the same objectives. We find in the case of a deuterium–tritium plasma that the use of hydrogen results in a degradation of the propulsive capability of the system, but we find it quite suitable for an engine that burns a mixture of deuterium and helium 3. The same results can be achieved by simply increasing the density of the injected plasma without encountering major adverse consequences. Because of engineering considerations, however, the use of a hydrogen propellant may prove to be inevitable if no other means are found to protect the walls of the reactor chamber against large heat loads.

Nomenclature

C_p = specific heat
c_0 = constant, Eq. (2)
d = one-way travel distance
E_{in} = energy of injuected plasma
E_0 = fusion energy deposited in plasma
F = thrust
g = gravitational acceleration
I_{sp} = specific impulse
L = length of engine
m_f = dry mass of vehicle
m_h = mass of hydrogen molecule
n = plasma particle density
n_H = hydrogen molecular density
P_f = fusion power
P_h = pre-heat power
P_i = injection power
P_{in} = power to injector
P_n = neutron power
P_r = radiated power
p_0 = constant, Eq. (2)
Q = fusion energy multiplication
Q_c = critical Q value
R = plasma mirror ratio
s_0 = constant, Eq. (2)
T = plasma temperature
T_H = hydrogen temperature
T_{H0} = hydrogen inlet temperature
u = hydrogen flow velocity
v_{th} = plasma thermal velocity
η_D = direct converter efficiency
η_i = injector efficiency
η_t = thermal converter efficiency
ρ = hydrogen gas mass density
τ = plasma confinement time
τ_H = hydrogen residence time
τ_{RT} = round-trip time

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I. Introduction

ONE of the major difficulties in man's exploration of space is the lack of propulsion systems that would allow such missions to be undertaken in reasonably short times to minimize exposure to galactic radiation and to preserve the mental and physical well being of the crew. A manned mission to Mars, for example, could well be carried out with chemical propulsion and/or nuclear thermal propulsion, but at a very high cost because of the massive amounts of fuel (perhaps several times the dry weight of the transfer vehicle) required to accomplish the mission[1] as well as to the lengthy travel time. By contrast, the fusion system presented in this paper will have a specific impulse that is at least two orders of magnitude higher than that of nuclear thermal propulsion and whose fuel weight constitutes a small fraction of the total weight, regardless of when the missions are initiated. In effect, the use of such a system virtually eliminates all mission window constraints and effectively allows unlimited manned exploration of the solar system and beyond.

The device in question is the gasdynamic mirror (GDM),[2] which utilizes a simple magnetic mirror geometry to provide adequate confinement for a hot plasma to undergo fusion reactions while allowing a fraction of its charged particle population to escape through the end to generate thrust (see Fig.

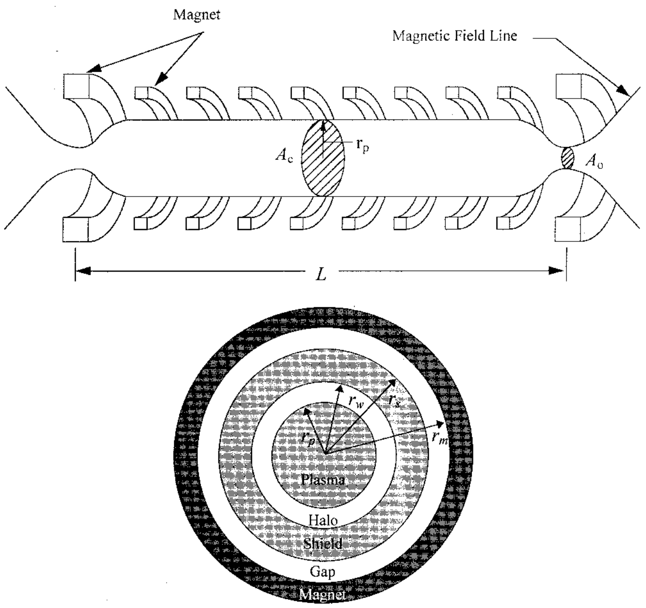

Fig. 1 Schematic and cross-sectional view of the gasdynamic fusion propulsion system.

1). Unlike the device that was studied for decades as a potential terrestrial power reactor where the plasma is described as collisionless, GDM will operate at a significantly high density to make the collision mean free path (λ) much shorter than the machine length L. Under these conditions the plasma behaves much like a fluid, and the escape of the plasma from the system is analogous to the flow of a gas into a vacuum from a vessel with a hole. Accordingly, the flow is governed by the gasdynamic equations that yield for the particle lifetime in such a device the following expression:

$$\tau = RL/v_{\text{th}} \tag{1}$$

where R is seen by the plasma (and related to the vacuum mirror ratio[2]). When an appropriate set of conservation equations are used to evaluate the performance of the systems, it can be shown[3] that the length of the device scales with the plasma parameters in accordance with the following relation:

$$L = \frac{E_{\text{in}} - 2T}{nRc_0[p_0 + s_0T^{3/2} - \frac{1}{4}\langle\sigma v\rangle(E_{\text{in}} + E_0)T^{-1/2}]} \tag{2}$$

The value of E_{in} can be established by first noting that P_i can be expressed in terms of P_f through the Q value of the reactor, namely,

$$Q = \frac{P_f}{P_i} = \frac{\frac{1}{4}n^2\langle\sigma v\rangle E_f}{nE_{\text{in}}/\tau} \tag{3}$$

where $\langle\sigma v\rangle$ is the velocity-averaged fusion reaction cross section, and E_f is the energy produced by the fusion reaction, which in the case of deuterium–tritium (D–T) is 17.6 MeV. The previous analysis reveals that the length of the device decreases with increasing density and mirror ratio. It also shows that the length decreases with decreasing Q, and appears to reach a minimum in all cases at a temperature of about 10 keV when a D–T fuel cycle is used. These facts show in a dramatic fashion why GDM is particularly suited for propulsion, because, unlike the terrestrial power reactor, it requires a relatively small Q, which is easier to attain, and can also have the size and symmetry that allows for ease of assembly on Earth or in space.

The parameters of a seemingly attractive GDM are shown in Table 1 for D–T and D–He^3 fuel cycles.

In obtaining the results given in Table 1, we used Eq. (2) and utilized the Q value obtained from Eq. (4), noting that one-half of the charged particle power emerges through one mirror to yield the thrust power, while the other half is allowed to escape from the opposite end to the direct converter. The fractions of particles escaping through each end can, in principle, be controlled by adjusting the mirror ratio for that end. The masses of the magnets needed to confine the plasma were based on superconducting magnets sustained by a current density of 250 MA/m^2. Although the central field of 9.21 T for the D–T case is within present-day technology, the mirror field may not be because of the high mirror ratio invoked in this example. In the next section we will examine the impact of reducing the mirror ratio on the performance of the system and how it can lead to magnets that may be achievable in the near future. Reference 2 should be consulted for the procedure used in calculating the various quantities given in Table 1. It should also be noted that a value of β (ratio of plasma pressure to magnetic field pressure) near unity was also employed because of the assumption of near complete hydromagnetic stability (see Sec. II). This may appear to be high when viewed in the context of some recent mirror experiments where the plasma may be relatively collisionless. Because GDM is highly collisional the improvement of axial confinement caused by an increase in mirror ratio under the influence of large plasma beta has been documented. The feasibility of $\beta \sim 1$ plasma confinement in this device has been demonstrated.[4] The engine mass consists of that pertaining to the GDM reactor plus that of the injector that supplies heat to the burning plasma. Of special significance in this regard is the amount of injected power, which in both instances exceeds gigawatts. Such large amounts of power can perhaps be supplied only by a fission reactor, which if utilized would truly exacerbate the total mass of the vehicle, or by relying on the fusion reactor itself to generate enough power to sustain itself. The latter approach appears to be a reasonable one, especially if it does not result in enormously large Q values that would render the propulsion GDM system as unfeasible as the terrestrial power reactor. To calculate the critical Q value that would obviate the need for an external power source we follow the power flow diagram shown in Fig. 2.

Table 1 GDM parameters[a]

Parameter	D–T	D–He^3
Plasma density, cm^{-3}	1.0×10^{16}	1.0×10^{16}
Plasma temperature, keV	10	60
Plasma radius, cm	5	5
Plasma length, m	44	1297
Confinement time, s	4.07×10^{-3}	4.92×10^{-2}
Central magnetic field, T	9.21	24.73
Fusion power, MW	2.730×10^3	5.675×10^4
Bremsstrahlung power, MW	58.17	1.703×10^4
Synchrotron radiation power, MW	18.94	4.205×10^4
Neutron power, MW	2.183×10^3	6.213×10^3
Thrust, N	2.512×10^3	1.437×10^4
Thrust power, MW	1.351×10^3	1.894×10^4
Injection power, MW	2.233×10^3	4.643×10^4
Engine mass, mg	101	3015
Total vehicle mass, mg	422	4434
Specific power, kW/kg	13.40	6.28
Specific impulse, s	1.268×10^5	3.106×10^5
Mars round-trip, days	169	228

[a] $\beta = 0.95$, $Q = 1.222$, $R = 100$.

It can be shown, in a straightforward manner that this critical Q value, namely Q_c, can be written as

$$Q_c = \frac{1 - \frac{1}{2}\eta_i\eta_D}{\frac{1}{2}\eta_i\eta_D - (P_{\text{H}}/P_f) - [(P_n + P_r)/P_f](\frac{1}{2}\eta_D - \eta_t)\eta_i} \tag{4}$$

where P_c is the charged particle power that emerges from one of the mirrors to go directly to the direct converter to be converted into electric power. We have included the preheat component to address the potential use of hydrogen for thrust enhancement (see Sec. II) of GDM. Such a device can be an

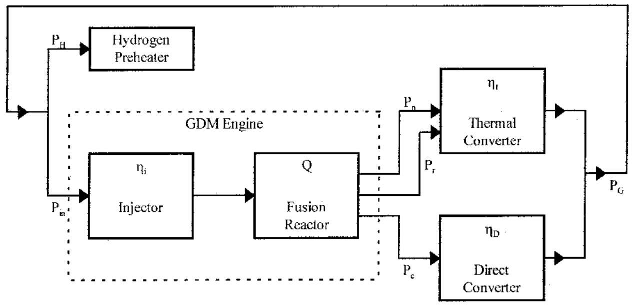

Fig. 2 Power flow diagram for the GDM rocket.

electrothermal unit where electric power is used to preheat a hydrogen gas before injecting it into the reactor chamber to be further heated by the radiation emitted by the plasma. If we set $P_H = 0$ and use $\eta_i = 1$, $\eta_t = 0.45$, and $\eta_D = 0.90$, we find from Eq. (4) that $Q_c = 1.222$, which is the value shown in Table 1 for both fuel cycles. This particular Q value is independent of the fuel mixture used in the reactor and occurs only when η_t is exactly one-half that of η_D. This is a consequence of the fact that only one-half of the charged particles in the system are assumed to emerge from one of the mirrors to produce thrust, while the other half is utilized via the direct converter to produce electric power. It is clear from Table 1 that the GDM propulsion device is capable of producing large values of I_{sp}, well in excess of 10^5 s, but at moderate thrusts. To see how effective these propulsive capabilities are we apply them to a manned mission to Mars. We employ a constant thrust, constant I_{sp}, continuous burn acceleration/deceleration type of trajectory and use the linear distance from Earth to Mars that corresponds to the configuration when the Earth lies on the line between the sun and Mars (approximately every 26 months). The τ_{RT} in this case can be written as[5]

$$\tau_{RT} = (4d/gI_{sp}) + 4\sqrt{(dm_f/F)} \tag{5}$$

Equation (5) neglects the effects of gravity of the planets involved as well as that of the sun. It also ignores the change in the Earth's position during the flight, and although a more accurate trajectory may be desirable it is believed that these analytically produced results are sufficiently meaningful in assessing the performance of the propulsion system. For the D–T-burning GDM the round-trip time is 169 days, whereas for the D–He^3 case the time is 228 days. It is evident from Eq. (5) that τ_{RT} decreases with increasing I_{sp} and increasing thrust, and while both systems generate very impressive specific impulses they both lack in sizable thrusts. Not only are high thrusts desirable from the trip time standpoint, but also from the need to lift sizable objects into space. This aspect will be addressed in the next section, but further observations concerning the performance of the GDM engine should be made before dealing with thrust enhancement.

II. Stability Considerations

Of special importance in the operation of GDM is the question of plasma stability. Unlike the collisionless terrestrial simple mirror machine that was beset by a hydromagnetic (MHD) instability called the flute instability that arises because of the concave magnetic curvature in the direction of the plasma, GDM is found to be totally stable against this dangerous mode.[6] Stabilization arises from the presence of plasma in the throat of the mirror where the field curvature is favorable (convex) as well as from finite Larmor radius effects. These effects have been theoretically predicted[7] and experimentally confirmed,[8] leading to the general conclusion that the gasdynamic mirror can be totally stable against these modes. With a large aspect ratio (i.e., L/r_p) characterizing the GDM devices shown in Table 1 it is clear that the field lines throughout most of the engine have neutral curvature, and only in the transition region from the central section to the mirror throat does the field exhibit unfavorable curvature. Since the criterion[9] for stability involves an integral of field curvature over the full length of flux tubes it is clear that with the aid of the expansion region of the nozzle the field curvature over the plasma will on the average be favorable and the flute mode stable. In addition to the MHD modes the simple mirror is susceptible to microinstabilities that derive their energy from deviations of the plasma distribution function from thermodynamic equilibrium. Most prominent among these are the loss cone[10] instability and that which is associated with anisotropy.[11] The first arises when plasma particles with large velocities along the magnetic field escape through a cone in velocity space leading to a depletion in the velocity distribution function. As noted earlier this is not likely to happen in GDM since the plasma is highly collisional and the necessary condition, $L > \lambda/R$, guarantees against effective scattering through an angle of the order of the loss cone angle ($\sim 1/\sqrt{R}$). Under these conditions the instability in question will not adversely affect the longitudinal confinement of the plasma represented by Eq. (1). If the plasma is injected in the midplane of the device, perpendicular to the magnetic field, then strong anisotropy in the ion distribution function will arise in the low-magnetic-field region and many kinetic instabilities[11] could be excited there. However, most of the unstable modes will be stabilized because of the radial inhomogeneity, which leads to a violation of the wave–particle resonant interaction required to trigger these modes, and those that are not stabilized will not perhaps have catastrophic consequences since the time for fast ions to slow down on the electrons is quite short. The general tendency revealed in many mirror experiments shows that in the case of a skew injection the microstability of the plasma is significantly improved when compared to that of a perpendicular injection. In the absence of any turbulence the particle transport across the magnetic field in an axisymmetric mirror such as GDM would be classical and negligibly small under all realistic plasma conditions. This can be demonstrated by noting that classical across field diffusion can be viewed as a random walk with a step size of a Larmor radius, caused by collisions between particles. For the case illustrated in Table 1, it can easily be shown that the characteristic time for radial transport is at least an order of magnitude longer than that characterizing axial confinement, and as a result the corresponding diffusion can be safely ignored. For that reason the relevant confinement time under consideration in this analysis is that associated with the longitudinal containment reflected in Eq. (1).

The results displayed in Table 1 are for a mirror ratio R of 100, making the vacuum field strength at the mirror quite high, especially for the D–He^3 fuel cycle. Such fields are out of

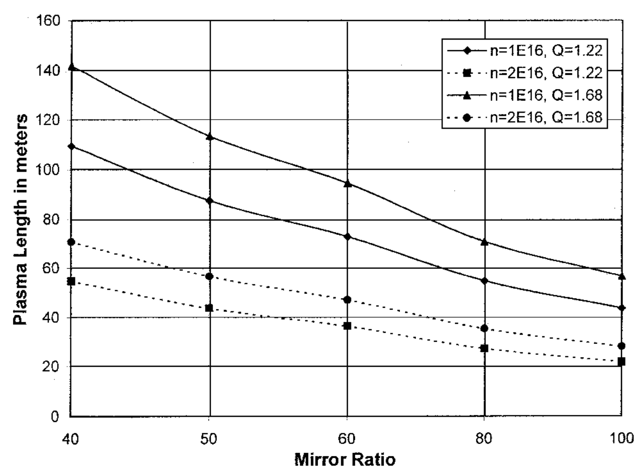

Fig. 3 Plasma length vs mirror ratio for D–T.

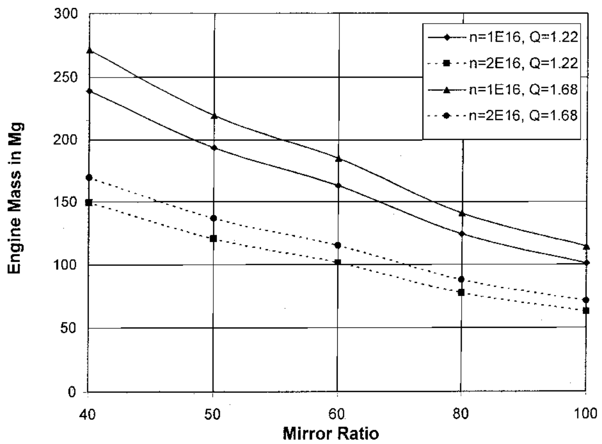

Fig. 4 Engine mass vs mirror ratio for D–T.

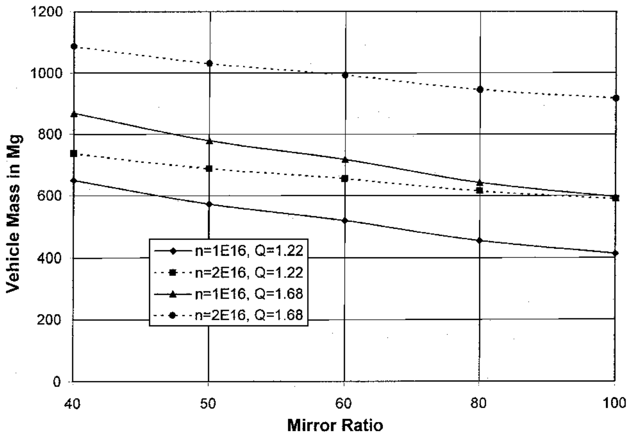

Fig. 5 Vehicle mass vs mirror ratio for D–T.

reach with present-day technology but can become feasible as more progress is made in superconducting magnet technology. Reducing the mirror ratio will have a salutary effect in this regard, but it will also contribute in a positive manner to the MHD stability discussed earlier. When the mirror ratio is reduced the confinement time becomes proportionately smaller [see Eq. (1)], and more plasma will reside in the throat region adding the necessary ingredient to the stabilization process described earlier. But that does not happen without penalty as revealed in Figs. 3–5, which depict the change in the length, engine mass, and total vehicle mass with mirror ratio. Clearly, the smaller the reduction in R, the more modest the increase in the length and mass of the vehicle, and the only uncertainty that remains concerns the extent to which R can be reduced without adversely affecting the performance of the system while preserving the stabilization mechanism.

III. Thrust Enhancement of GDM

We noted earlier, and revealed in Table 1, that the GDM propulsion system produces modest thrusts while generating very large specific impulses. It also generates large amounts of radiation, which, if not utilized, will simply fall on the wall of the reactor chamber precipitating very high heat loads. The total radiated power (bremsstrahlung plus synchrotron) in the DT burning system is about 77 MW, whereas in the D–He^3 it is about 59 GW, and when such radiant energy is used to heat a hydrogen propellant that is exhausted through a nozzle a significant increase in the thrust will result. We address this question first by using a simple model that assumes that all radiation is absorbed by a hydrogen stream that is injected into the reactor chamber at a certain inlet temperature and allowing no heat flow to the wall, or mixing between the plasma and hydrogen as illustrated in Fig. 6. This implies that the core

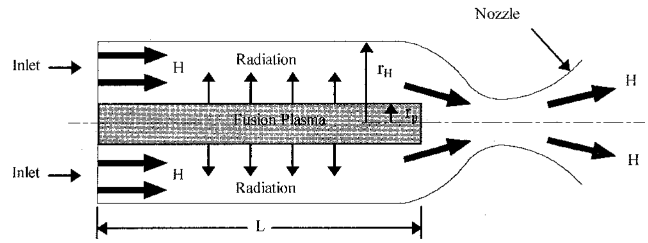

Fig. 6 Thrust-enhanced GDM configuration.

plasma is transparent to this radiation, which for the conditions under consideration, has an absorption mean free path much larger than the dimensions of the system. It also uses a (seeded) hydrogen that is totally opaque. In the more rigorous model to be introduced shortly, the appropriate hydrogen opacity is introduced through the Rosseland mean absorption coefficient in the energy equation.

If we ignore the emissivity of the hydrogen gas, assume steady-state conditions, and neglect heat transfer in the direction of motion as is usually done for heat conduction in moving fluids, then the appropriate energy balance equation is given by[12]

$$\rho c_p u \frac{dT_H}{dx} = P_r \tag{6}$$

where P_r is the radiated power per unit volume or the heat source and dT/dx is the temperature change in the direction of flow. Noting that $\rho = n_H m_H$, Eq. (6) can be rewritten as

$$c_p \frac{dT_H}{dt} = \frac{P_r}{n_H m_H} \tag{7}$$

which upon integration becomes

$$T_H = T_{H0} + \tau_H \frac{P_r}{c_p n_H m_H} \tag{8}$$

where T_{H0} and τ_H are given by

$$\tau_H = (L/u) \sim (L/\sqrt{T_H}) \tag{9}$$

We apply the previous analysis to the GDM case and obtain the results displayed in Table 2 for an inlet temperature of 3000 K and the two fuel cycles given in Table 1. In both instances the effective thrust of the engine is increased significantly relative to the unenhanced case, but because of the much larger hydrogen mass flow rates (3 and 270 kg/s) compared to the core plasma flow rate of about 0.002 kg/s, the effective specific impulse is decided almost totally by the hydrogen propellant and that represented an almost two orders of magnitude drop. When both of these factors are taken into account in calculating the round-trip to Mars we find an increase in travel time of about 214 days in the case of D–T and 55 days in the D–He^3 case.

When a more realistic thermal hydraulic model[13] that takes into account heat flow to the wall where the temperature is maintained at 3000 K is used, the results shown in Table 3 are obtained. With this computational approach, which solves the appropriate hydrodynamic conservation equations, we have examined several cases where the hydrogen-layer thickness was varied from 2 to 50 cm and calculated, among other things, the heat power to the wall. We see from Table 3 that the thrust contribution of the propellant itself is significantly higher than that of the core plasma shown in Table 1. When the two are combined, the effective thrust for the 5-cm hydrogen-layer case of a D–T-burning GDM is about 35 kN, which is about a factor of 15 higher than the unenhanced case, but the effec-

Table 2 Parameters for the simple thrust enhancement model

Parameter	D–T	D–He^3
Radiative power, MW	77	59×10^3
Hydrogen flow rate, kg/s	3.00	270.00
Inlet temperature, K	3000	3000
Hydrogen layer, cm	5	5
Exit temperature, K	4325	14,218
Preheat power, MW	1.746×10^2	1.571×10^4
Effective thrust, kN	32.53 (2.512)[a]	3.607×10^3 (14.37)[a]
Effective I_{sp}, s	1.11×10^3 (1.268×10^5)[a]	1.36×10^3 (3.106×10^5)[a]
Trip time to Mars, days	383 (169)[a]	284 (228)[a]

[a]Quantities in parentheses are for unenhanced system.

Table 3 Results of the thermal hydraulic model

	DT, hydrogen-layer thickness, cm					D–He^3, hydrogen-layer thickness, cm				
Parameter	2	5	10	25	50	2	5	10	25	50
Hydrogen mass flow rate, kg/s	4.80	3.00	2.35	1.95	2.00	360	270	230	200	180
Hydrogen specific impulse, s	1052	1117	1164	1200	1195	1680	1845	1958	2071	2161
Hydrogen thrust, kN	49.5	32.8	26.8	22.9	23.4	5930	4880	4410	4060	3810
Preheat power, MW	237	148	116	96	99	17.7×10^3	13.3×10^3	11.3×10^3	9.9×10^3	8.8×10^3
Power to wall, MW	7.5	7.4	7.4	7.6	7.7	5900	5800	5900	5800	5900
Hydrogen exit temperature, K	3867	4364	4775	5259	5510	6870	8540	10,320	13,280	15,610
Hydrogen average temperature, K	3454	3729	3930	4077	4058	5930	6650	7130	7690	8200

tive specific impulse drops precipitously by a factor of almost 150. The same table also reveals that the thrust decreased with increasing thickness while the power to the wall remained effectively the same. On the other hand, the specific impulse generated by the hydrogen layer seems to increase slightly with increasing thickness up to a point (25 cm), then it declines. In all instances, however, the effective specific impulse reflects a drop of well over two orders of magnitude relative to the unenhanced case, primarily as a result of the very small core plasma mass flow rate.

It is interesting to note at this juncture that the results of the simple model embodied in Eqs. (6–8), for such parameters as the thrust, preheat power exit, and average propellant temperature, etc., are no more than 15% off of those predicted by the more accurate thermal hydraulic model that allows for temperature gradients as well as heat flow to the wall. Although the hydrogen specific impulse is related to the square root of the exit temperature by the simple model, much of the difference in the two results is attributed to the dissociation of the hydrogen molecule that is accounted for only in the computational model. In short, the simple model is especially useful when only gross effects are sought. It is also worth noting from Table 3 that about 10% of the total radiation power ends up at the wall (by design) and when that is used to calculate the heat wall loading we find that for the 5-cm hydrogen layer this quantity is 0.27 MW/m^2 for the DT case, and 4.67 MW/m^2 for the D–He^3 case; values that are deemed to be well within acceptable values from the materials standpoint. It is also worth noting that the hydrogen mass flow rates were selected to ensure the integrity of the wall as described earlier, while guarding against triggering the Kelvin–Helmholtz instability,[14] which arises when one fluid (the propellant) flows past another (the plasma core) in the presence of a gravitational force. The hydrogen, in the case at hand, is introduced at a sufficiently high pressure that makes its density comparable to or larger than that of the hot plasma. When that fact is coupled to the flow velocity noted earlier it is possible that short wavelength modes can become unstable, leading to localized turbulence. Such instability can, however, be stabilized by placing the system in an axial magnetic field with a magnitude of about 0.2 T, well below the central field value of 9.2 T. Therefore, such a situation is not likely to occur in GDM because of the tension that the magnetic field exerts at the boundary between the plasma and the hydrogen, which at these operating temperatures remains unionized and almost oblivious to the presence of the confining magnetic field.[15]

The preheat power is the power required to heat the hydrogen up to its inlet temperature of 3000 K. This can be achieved by regeneratively cooling the nozzle and/or other system components, provided there is enough power. In the absence of such power the fusion Q value should be increased to accommodate this need (see Sec. IV). As both Tables 2 and 3 reveal, the majority of the thrust is because of the preheating of the hydrogen in the D–T case and to a much lesser extent in the D–He^3 case. In all instances additional thrust is gained because of flow in the chamber where heating by the radiated power takes place. The maximum attainable temperature of the hydrogen is set by the heat flux, wall temperature, and hydrogen-layer thickness. It is independent of flow rate because as soon as the hydrogen reaches its maximum temperature it is saturated with heat such that additional energy input flows through the hydrogen to the wall. The hydrogen temperature at the wall is fixed by the wall temperature, the temperature gradient is fixed by the heat flux, and the maximum temperature is determined by the gradient and the layer thickness.

The results given in Table 3 were calculated by setting the limit on power conducted to the wall at 10% of the total power input to the hydrogen. Lower flow rates will result in only slightly higher hydrogen specific impulse, but lower thrust in proportion to the flow rate. It appears on the basis of this thermal hydraulic model that the only way to get significantly higher specific impulse out of the hydrogen is to make the radial heat flux higher, i.e., the same power over a shorter core length. Increasing the wall temperature is not really an option and increasing the hydrogen-layer thickness helps only marginally. In fact, if it is made too large it will have a negative affect, as can be seen from the 50-cm case shown in Table 3.

IV. Propulsive Capability of a Thrust-Enhanced GDM

We noted earlier that in the absence of preheat power derived from regeneration cooling of the nozzle or other components of the system, another external means will have to be used to heat the hydrogen propellant before it enters the reactor chamber. Such heating can be provided by an electrothermal unit powered by the fusion reactor itself as illustrated in Fig. 2. Since that represents an additional power that the fusion

Table 4 Propulsive parameters of GDM with externally heated propellant

Parameter	D–T	D–He^3
Gain factor, Q	1.387	1.93
Plasma density, cm^{-3}	1.0×10^{16}	1.0×10^{16}
Plasma temperature, keV	10	60
Plasma length, m	52	2179
Plasma radius, cm	5	5
Central magnetic field, T	9.21	24.73
Hydrogen-layer thickness, cm	5	5
Hydrogen mass flow rate, kg/s	3	270
Hydrogen exit temperature, K	8079	21,950
Hydrogen preheat power, MW	174	1.57×10^4
Fusion power, MW	3.25×10^3	9.54×10^4
Bremsstrahlung power, MW	69	2.86×10^4
Synchrotron radiation power, MW	23	7.07×10^4
Neutron power, MW	2.60×10^3	1.04×10^4
Hydrogen preheater mass, mg	3.50	459
Engine mass, mg	114	4232
Total vehicle mass, mg	484	6657
Effective thrust, kN	32.53	4468×10^3
Effective thrust power, MW	1.50×10^3	5.428×10^4
Specific power, kW/kg	11.87	4.146
Effective I_{sp}, s	1.11×10^3	1.688×10^3
Mars round-trip, days	383	234

[a]$\beta = 0.95$, $R = 100$.

reactions must supply, the Q value of the system must accordingly increase to meet that demand. With the aid of Eq. (4) and the same component efficiencies as before, we find that the new Q value for the D–T system is 1.387, and for the D–He^3 system it is 1.93. When these values are incorporated in the dynamic equations of the system the results shown in Table 4 emerge. When compared to the unenhanced systems given in Table 1 we see once again a sharp increase in thrust when a hydrogen propellant is used and a corresponding drop in the specific impulse. These changes appear to be more dramatic in the D–T case since they result in a sizable increase in travel time, but at a modest change in the length and the total dry mass of the vehicle. The opposite appears to be true in the D–He^3 case where the travel time remained virtually the same, but at the expense of enormous increases in the size and mass of the vehicle. This is attributed to the large amounts of radiated power generated in the D–He^3 case, which operates at a much higher plasma temperature that results in larger lengths, magnetic fields, etc. These in turn lead to very large thrusts at a more moderate reduction in the specific impulse, which translates to quicker trip times. Based on the data given in Table 3, it is clear that the use of a preheated hydrogen propellant to augment the thrust of a D–T-burning GDM is perhaps not the most effective way of dealing with a low-thrust engine, even though it may lead to the protection of the chamber walls from high heat fluxes. For the D–He^3 case the use of a hydrogen propellant appears to be compatible with the overall performance characteristics of the vehicle, but the unacceptably large systems that emerge render their near-term potential use for propulsion almost unthinkable for economic, if not for technological, reasons.

V. Thrust Augmentation by Plasma Density Increase

As an alternative to the thrust enhancement approaches presented earlier we consider a more direct approach that circumvents the use of a secondary propellant. We focus on achieving the same objective by changing the property of the hot plasma itself, which in GDM serves as both fuel and propellant. Perhaps the most logical approach is to increase the plasma density where a one order of magnitude increase results in a corresponding increase in the thrust and a similar reduction in the length according to Eq. (2). To see how such a change impacts the other parameters of the system we have re-examined the two GDM devices given in Table 1 at a higher density and the results are displayed in Table 5. We readily note, by comparing with the results in Tables 2 and 4 for D–T, that the thrust enhancement by this method is almost identical to that of the previous approaches, but with no degradation of the propulsive capability of the system.

Table 5 Thrust enhancement by plasma density increase[a]

Parameter	D–T	D–He^3
Plasma density, cm^{-3}	1.0×10^{17}	1.0×10^{17}
Plasma temperature, keV	10	60
Plasma radius, cm	5	5
Plasma length, m	4.378	130
Confinement time, s	4.07×10^{-4}	4.92×10^{-3}
Central magnetic field, T	29.114	78.20
Fusion power, MW	2.730×10^4	5.675×10^5
Bremsstrahlung power, MW	5.817×10^2	1.703×10^5
Synchrotron radiation power, MW	1.894×10^2	4.205×10^5
Neutron power, MW	2.183×10^4	6.213×10^4
Thrust, N	2.512×10^4	1.437×10^5
Thrust power, MW	1.351×10^4	1.894×10^5
Injection power, MW	2.233×10^4	4.643×10^5
Engine mass, mg	32.8	2395
Total vehicle mass, mg	2458	9813
Specific power, kW/kg	412	79
Specific impulse, s	1.268×10^5	3.106×10^5
Mars round-trip, days	131	108

[a]$\beta = 0.95$, $Q = 1.22$, $R = 100$.

In fact, it can be seen that in spite of the shorter but more massive vehicle, the round-trip time to Mars was reduced from 169 to 131 days. More dramatic perhaps is the very large increase in the specific power of the device (13.4–412), considered by many as a true measure of the efficacy of any propulsion system. The same trends can be seen in the D–He^3 case where the reduction in travel time is even more dramatic. Although the length of the system was reduced by an order of magnitude, the total mass was only nearly doubled and the specific power was enhanced by a factor of about 15. This approach leaves open, however, the question of protecting the wall from the heat fluxes that increase by an order of magnitude because of density increase. Other approaches must be found to address this question and a recent proposal[16] calls for the use of a lithium coating of the chamber wall. During operation of the engine the high heat fluxes and neutron wall loading will cause the lithium to liquify. A slow rotation induced in the vehicle will produce centrifugal forces that will force the lithium to remain in place, creating in essence a liquid first wall. Not only will the material problems associated with radiation damage be considerably reduced, but also the liquid lithium will serve as a coolant to heat a gaseous working fluid that can be utilized in the thermal conversion component of the power cycle illustrated in Fig. 2. A more detailed study of this and other potential remedies to this problem are indeed necessary if GDM is to become the propulsion system for future space exploration.

VI. Conclusions

We have examined means by which the thrust in the gasdynamic mirror fusion propulsion system can be enhanced. We note that under normal operating conditions the plasma in this device can be stably confined to allow enough fusion reactions to take place to produce the desired propulsive capability while simultaneously generating the power needed for the system to be self-sustaining. Under such conditions GDM produces very large specific impulses, in excess of 10^5 s, but at moderate thrusts since the propellant, which is also the fuel, consists of light hydrogenous ions. Large thrusts are desirable not only for the purpose of lifting heavy objects in space but also because they contribute to the reduction in space travel time.

The first approach we examined consisted of utilizing a hydrogen propellant that is introduced into the reactor chamber at very high pressure, heated by the radiation emitted by the fusion plasma, and then exhausted through a nozzle to provide the additional thrust. Using first a simple radiation heat transfer model that ignores gas emissivity and heat flow to the wall, we calculated the thrust and the specific impulse contributions of the propellant. We find that the thrust enhancement was significant but offset by the drastic reduction in the specific impulse of the total system. When a more comprehensive thermal hydraulic model that accounts for heat transfer and wall temperature limitations was utilized, the trends predicted by the simple model were confirmed in that the significant improvements in the thrust were more than offset by the sharp decline in the specific impulse of the engine and a corresponding increase in travel time, especially for the D–T burning engine. In the case of the D–He^3 system where the radiated power was significantly larger, the change in the propulsive capability of GDM was quite minor, but the total mass of the vehicle became prohibitively large. In both instances it was observed that the presence of a hydrogen layer between the plasma core and the chamber wall contributed significantly to the reduction of the wall heat loading and the associated materials radiation damage problems.

The other approach examined in this paper consisted of simply increasing the injected plasma density where equally effective results could be obtained. Although the approach resulted in larger vehicle masses it also resulted in shorter engines and much reduced trip times. Based purely on performance one would tend to conclude that the increasing plasma density approach is more desirable since it does not lead to a degradation of the propulsive capability of GDM, although it does leave open the question of radiation damage to the wall. Unless this concern is adequately addressed through the use of, for example, a liquid first wall, engineering and material considerations may necessitate the use of buffer zone to moderate the heat flow and that may make the use of a hydrogen propellant inevitable.

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