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Electrodeless Plasma Thruster with Self-Generated Electric Field

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An "electrodeless" plasma thruster that generates its own electric potential for utilization in the acceleration of its propellant is proposed. It is based on the gasdynamic mirror (GDM) magnetic concept in which the confined plasma would be of such density and temperature as to make the collision mean free path of its ion species much shorter than its 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 into vacuum from a vessel with a hole. Upon inserting the plasma into this magnetic bottle, the electrons escape rapidly through the mirrors due to their small mass, leaving behind an excess of positive charge that manifests itself in a positive electrostatic potential. The electric field generated by this potential accelerates the ions while slowing down the electrons until both species leave the mirror at equal rates, thereby producing a charge-neutral propellant beam (a very desirable effect indeed). Moreover, the GDM plasma thruster will be magnetically "asymmetric" to further control the flow of the propellant, and in conjunction with adjustable input power it could provide variable specific impulse and thrust. This thruster may be viewed currently as a TRL 3 concept since some of the underlying physics has already been validated and could readily be advanced to TRL 5-6 in a matter of several years. Preliminary estimates reveal that with an input power of 50 kWe, such a thruster employing a Lithium propellant at a density of 10^{15} cm^{-3} can generate 124 eV electrostatic potential that could deliver about one Newton of thrust at a specific impulse of well over 7000 seconds, making it especially suitable for the science missions of the near future.

I. Introduction

It is often suggested that electric propulsion systems, especially the magnetoplasmadynamic (MPD) thruster, are the compact high power plasma accelerators that show promise for future exploration missions, particularly for piloted missions requiring megawatts of power and high specific impulse in order to transport humans to other planets. They rely on coaxial electrodes to generate the electromagnetic accelerating force in the case of the "self-field" MPD thrusters, and on a combination of that configuration and an external coil in the case of the "applied field" MPD thrusters. In all instances, however, the fact remains that this (and other EP schemes) suffer from serious problems associated with issues of heat rejection and electrode erosion over extended periods of steady-state operation. These problems have proven to be more critical than the anticipated plasma dynamics issues – though serious in their own right – in developing an engineering design for these schemes. Most current experimental research on promising EP concepts is limited to input powers of ≤ 100 kWe with the hope of eventually developing nuclear power systems that could provide megawatts of power needed for the interplanetary missions noted above.

II. Underlying Principles

An "electrodeless" plasma thruster that generates its own electric potential for utilization in the acceleration of its propellant is proposed. It is based on the gasdynamic mirror (GDM) magnetic concept in which the confined plasma would be of such density and temperature as to make the ion-ion collision mean free path (mfp) much shorter than its 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 into vacuum from a vessel with a hole.

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The magnetic configuration of GDM is that of a simple magnetic mirror in which the magnetic field strength at the mirrors is stronger than that in the central section. The underlying physics for a symmetric GDM (with equal magnetic field strength at both ends) have been studied previously.[1,2] The magnetic configuration of GDM allows the plasma to be confined long enough to be heated by injected power (such as microwave power) before it emerges through the mirror to produce thrust. Upon inserting the plasma into the magnetic bottle, the electrons escape rapidly through the mirrors due to their small mass, leaving behind an excess of positive charge that manifests itself in a positive electrostatic potential. The electric field generated by this potential accelerates the ions while slowing down the electrons until both species leave the mirror at equal rates, thereby producing a charge-neutral propellant beam (a very desirable effect indeed). Because hotter electrons produce larger electrostatic potential[0], hence larger accelerating electric field, the proposed thruster can be viewed as a variable thrust device if the input power source can be readily manipulated and adjusted to match the thrusting requirements. Moreover, the GDM plasma thruster will be magnetically "asymmetric" to further control the flow of the propellant, and in conjunction with adjustable input power it could provide variable specific impulse and variable thrust. With such asymmetry, the energy of the plasma escaping through the non-thrusting mirror can be recovered and converted at a very high efficiency into electric power that can be recycled back to the input power source.

III. Design Considerations

In an effort to circumvent the major magnetohydrodynamic (MHD) instability known as the flute or Rayleigh-Taylor macroscopic instability, the GDM thruster will have a large aspect ratio (length-to-diameter ratio) in order to minimize the concave (towards the plasma) curvature of the magnetic field lines along the length of the device which drives such plasma instability modes. Furthermore, large mirror ratios (magnetic field strength at mirror to that at center) along with the high collisionality manifested by the small mfp tend to close the "loss cone" region in velocity space of the plasma particles and prevent a major microinstability from arising. High collisionality also tends to isotropize the plasma particles temperature (mean energy) parallel and perpendicular to the field lines, thereby eliminating the source for another microinstability. Though not as dangerous as the MHD modes, these microinstabilities can lead to local turbulence and enhanced diffusion across the magnetic field lines. The MHD modes can however be particularly harmful since they can lead to plasma break-up in timescales shorter than those needed for confinement that allow for adequate heating by the external power source. In brief, there appears to be no major plasma stability problems that can prevent the proposed thruster from functioning effectively as described. This is consistent with several experimental observations in high beta (ratio of plasma pressure to magnetic field pressure) system that reveal no large scale instabilities that could lead to rapid plasma breakup.[3]

Although sizable magnetic fields would be required for the plasma confinement, mass minimization of the propulsion device can be achieved with the use of high-temperature superconducting magnets currently being investigated and hopefully developed in the time frame of interest. There are also other schemes under investigation that address large magnetic fields which also may come online in the same time frame for utilization in this thruster. With the impressive progress being made in the development of high power microwave sources (gigawatts of power at giga-hertz frequencies), the evolution of the GDM thruster into a megawatts device for deployment in cargo and human interplanetary missions appear to be very promising.

IV. Application to Mars Mission

We evaluate the mission performance (in terms of trip time and vehicle mass) of a nuclear-powered GDM thruster for a one-way Mars cargo mission carrying 90 metric tons (mT) of payload operating at 1.5 MWe using Lithium as propellant. These parameters were chosen in order to compare the results with those for a nuclear-powered MPD thruster[4], in which the authors provide a much more detail design than the present concept. Figure 1 illustrates the trip time versus the initial mass at low Earth orbit (IMLEO) for GDM systems with various Isp's. Three different specific masses for the nuclear power reactor were considered, with 5 mT/MWe achievable in the near future and 1 mT/MWe being long term technology. Figure 2 compares the GDM thruster with the MPD thruster.[4]

V. Conclusion

The proposed thruster may be viewed currently as a TRL 2-3 concept since some of the underlying physics (such as the gross plasma dynamics) of a cold dense plasma confinement in a magnetic mirror configuration has been explored at NASA's Marshall Space Flight Center (MSFC). It is expected that such a device can be readily

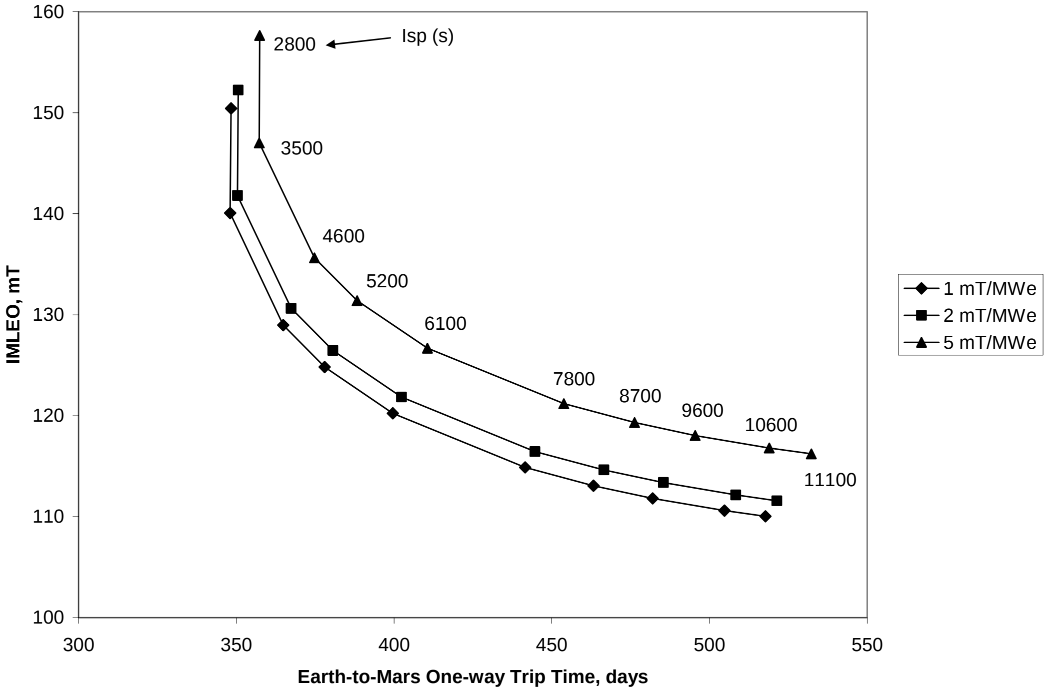

Figure 1. Mission performance for a 1.5 MWe Lithium GDM thruster. The three curves correspond to different nuclear power reactor specific mass; the Isp values apply to corresponding points on the curves.

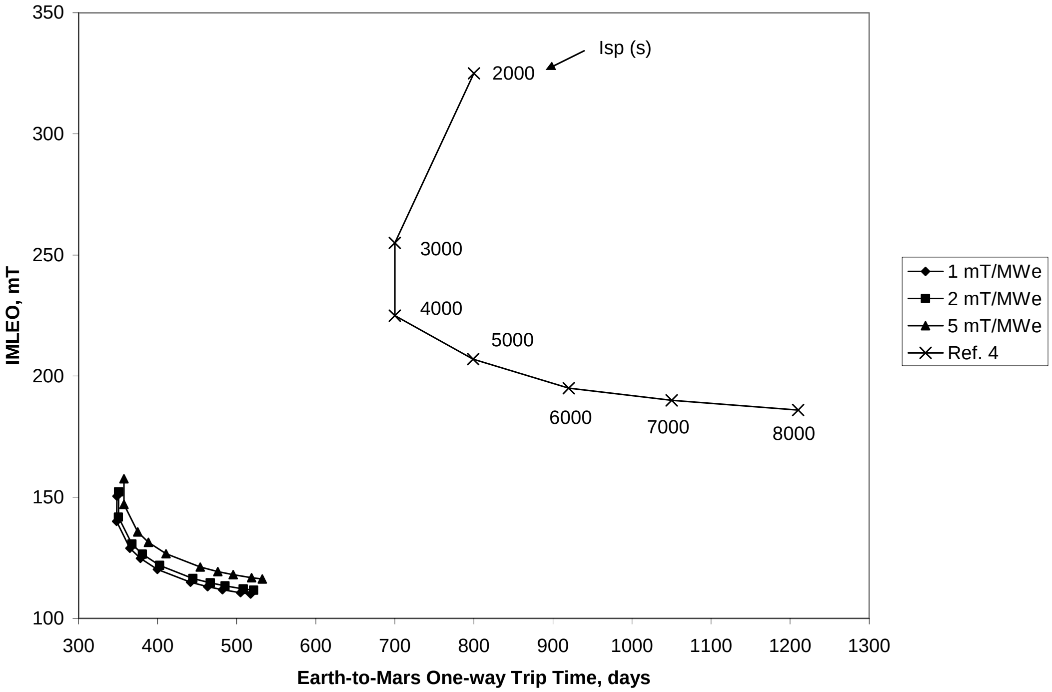

Figure 2. Mission performance comparison between the 1.5 MWe GDM thruster and the MPD thruster. The plots in Fig. 1 are reproduced in the lower left corner.

modified to function as a GDM plasma thruster and provide validation of the concept described above. It is also expected that progress can be made in the span of 2-4 years to produce a bench top hardware that would elevate the device to a TRL 5-6. Preliminary estimates reveal that with an input power of 50 kWe, a GDM plasma thruster with a Lithium propellant at a density of 10^{15} cm^{-3} can generate 124 eV electrostatic potential that could deliver about one Newton of thrust at a specific impulse of well over 7000 seconds. At about the same density using an Argon propellant the potential would be about 62 eV producing 2.4 Newtons of thrust at an Isp of about 2300 seconds. In both instances the thruster would be about 2 m long with a plasma radius of about 3 cm. Exploratory studies by the authors underscore feasibility of this concept and the timescale for its potential development.

References

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