Getter-Pumped Test Facility for High-Power, Long-Pulse MPD Thrusters

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The lack of data on the continuous operation of magnetoplasmadynamic (MPD) thrusters has inhibited development of improved designs for these devices. A significant obstacle in ground-based testing has been the inability to maintain sufficient vacuum in the testing vessel. The pumping speed required to maintain 10^{-4} Torr for a 5 g/s oxygen arc is ~ 10^7 l/s. A technique for achieving these pumping speeds continuously involves utilizing the gettering properties of titanium for such gases as hydrogen, nitrogen, oxygen, and hydrazine. In particular, a design is developed around a two-chamber differentially pumped system employing a practical-sized vacuum vessel and commercially obtainable, high throughput *e*-beam evaporators. It is shown that the required pumping speed can be maintained easily for periods of hours and is limited primarily by the necessity to reload the evaporators and maintain the vacuum vessel.

Introduction

REVIEWS[1,2] of work in the field of electric propulsion indicate that early assessments of the high performance of applied-field magnetoplasmadynamic (MPD) thrusters operating at power levels <100 kW were optimistic. The data were affected by the interaction between background tank gas and current loops extending along the magnetically confined plume.

Recent work has involved self-field thrusters that are less sensitive to gas pressure and chamber size since plume current loops extend only a few diameters downstream. Jahn et al.[3] and others[4-6] have studied the operation of this type of thruster at the high-power levels (~ 2 MW) necessary to provide dominance of magnetic over thermal effects but in a pulsed mode (0.2–2.0ms). Although this body of reliable data has provided information on performance, internal and external current patterns, and transition to the limiting regime of unsteady operation, the lack of a continuous operation capability has prevented realistic assessment of thruster lifetime.

The difficulty in developing a test stand for MPD thrusters involves the following issues: pumping requirements for high speed and throughput, power supply requirements, handling of the plume energy and waste heat, and the lack of plume data required for efficient test stand design.

An MPD arc operating at 5 g/s requires a throughput of 3000 Torr - l/s for a propellant such as oxygen. To maintain a vacuum of 10^{-4} Torr in a single chamber, the required pumping speed is 3×10^7 l/s. For ground-based life testing, unconventional pumping techniques[7,8] may be required. For hour-long pulse lengths, however, surface pumping, that is, gettering or cryopumping, is suitable. Gettering involves the chemical combination of certain reactive gases with fresh metal surfaces. Pulse length in limited is getter pumping by the evaporation rate and storage capacity of commerical sublimators and, in cryopumping, by the necessity for periodic regeneration. Cryopumps have the additional disadvantages of higher capital cost relative to getter pumping and sensitivity to heat radiated from the plume, although the latter problem could be resolved through engineering design. Other conventional vacuum technologies do not meet the pumping requirements.

The issue of power requirements for MPD thrusters is primarily one of cost and is discussed in Ref. 8. However, the high power level makes heat removal and component lifetime significant issues for long-pulse operation. The heat removal in test stand components that interact with the plume (as opposed to the MPD thruster itself) must be rated for >500 W/cm^2. Although this engineering is straightforward, sputtering by 100 eV particles of the plume will cause erosion, which ultimately limits component lifetime. If components are to have lifetimes exceeding the desired thruster life of several months, sputtering must be limited. Approaches involving gas targets and redeposition of sputtered material may be incorporated.[9]

Lastly, a design that is to operate continuously requires detailed engineering data on the plume, such as gas efficiency, stream temperature, directed velocity, and stream impurity level. Only qualitative and semiquantitative data are available in the literature.

These issues can be resolved in steps. Data obtained from a test stand capable of operation on the order of only minutes can form the basis for defining the engineering requirements necessary to develop a steady-state test stand. This is a considerable simplification since the problems associated with regeneration (or getter replacement), power supplies, and heat removal are easily handled. Only the issue of pumping speed needs to be addressed.

In this article, the general pumping characteristics of a thruster test stand capable of up to 5 g/s of getterable gases for hour-long intervals are discussed. In addition, the details of a feasible device based upon technical experience with fast hydrogen pumping[10,11] are presented.

Approach

The basic design utilizes the immediately available technology of titanium-sublimation pumping to achieve the high speed and throughput necessary to maintain 10^{-4} Torr in the vicinity of the thruster. Pulse length limitations arise from the titanium storge capacity and maximum evaporation rates of commercially available electron beam (*e*-beam) evaporators.[12] Gases gettered by titanium include hydrogen, nitrogen, and oxygen but not the noble gases.[13] Propellants such as a ammonia, hydrazine, water, carbon monoxide, and carbon dioxide can also be pumped as they are decomposed in the MPD arc.

In getter pumping, both pumping speed and throughput must be considered. The speed is the open area conductance, modi-

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fied by the sticking coefficient or probability per collision that an atom or molecule will stick with the surface. This coefficient varies for titanium at room temperature from 0.05 for hydrogen to 0.8 for oxygen and increases fivefold for hydrogen at 77 K. For getting oxygen, a room temperature surface provides a sufficient sticking coefficient. The effective pumping speed to a titanium surface of unfilled sorption sites of 300 K is 9 $l/s/cm^2$. Since the entire surface of the coated vacuum vessel can serve as a pump, high total speeds are possible. The effectiveness of such a pump for hydrogen has been demonstrated.[1] The walls of liners suspended inside the 14 m^3 vacuum vessel were held at 77 K by liquid nitrogen. Approximately 45 m^2 of liner surface was available for coverage by titanium sublimated prior to the 100 ms gas pulse. Measured pumping speeds greater than 1×10^6 l/s were achieved.

The throughput, or mass flow pumping rate, must be compatible with the titanium sublimation rate, since the titanium surface can maintain its pumping speed only so long as the coating is fresh. As the getterable gas is absorbed, the sites available for pumping molecules become filled. Thus, the pumping speed will decrease approximately linearly with the surface coverage. For a fixed throughput, a reduction in pumping speed results in increased background pressure. To maintain the required speed, the titanium must be replaced as the surface pumps the gas. Maximum titanium utilization is either one or two atoms per gas molecule.[13] Thus, for pumping 1 g/s of oxygen (utilization = 1), it is necessary to evaporate

$$1\ \text{g/s} \times \frac{\text{atomic wt titanium}}{\text{molecular wt oxygen}}$$

The titanium evaporation rates required to maintain an unsaturated monolayer on the pumping surface at a 5 g/s fuel ejection rate for various gases are given in Table 1.

For high throughput, titanium can effectively be deposited by electron beam evaporator. Large *e*-beam evaporators have been developed for use in laser isotope separation and industrial applications and are commercially available.[12] These units have a storage capacity of 100 kg and are able to sublimate 10 g/s of titanium. It should be possible to pump 5 g/s of oxygen with a single unit of this type for approximately 3 h. At this point, the titanium would have to be replaced. After several runs of this duration, the titanium would need to be removed from the walls, which we estimate will require 1 day of maintenance.

From the point of view of vacuum performance, maximum pumping speed with minimal titanium throughput, oxygen is the preferred fuel. Moreover, a recent comparison of the performance of an MPD arcjet with 11 different fuels[15] concludes that, except for its storability as a liquid, oxygen performance is "good" in four categories. In particular, contrary to expectations, thruster cathode erosion was comparable to that of argon and xenon and less than that of all others, including molecules containing carbon, hydrogen, and nitrogen.

A Design Example

The surface pumping characteristics of gettering can be utilized advantageously in the differentially pumped, two-section, titanium-gettered chamber illustrated in Fig. 1.

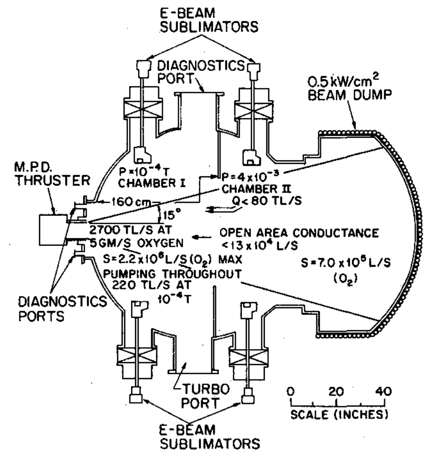
The pumping design assumes oxygen propellant exhausting at 5 g/s, a plume divergence half-angle of 15 deg, plume power of 2 MW, and a radiative heat loss of 1 MW.

The plume of exhaust material expands through the low-pressure chamber I through a nonscraping aperture into the high-pressure chamber II and the actively cooled dump region. All energetic plume particles are assumed to be transported though the aperture into chamber II where they ultimately recombine and cool to be pumped as room temperature molecules. Warmer molecules will have a higher open-air conductance to the wall, decreasing pressure in chamber II. The similarly increased conductance into chamber I is approximately compensated by this decreased pressure.

Table 1 Minimum evaporation rates required to pump 5 g/s throughput of various fuels[a]

Fuel	Titanium evaporation rate, g/s
Hydrogen	120
Water	27
Nitrogen	17
Oxygen	8

[a]Calculated from data of Table II, Ref. 14, p. 198.



M.P.D. THRUSTER PUMPING FACILITY
(PLAN VIEW)

Fig. 1 Proposed two-chamber, differentially pumped, test facility.

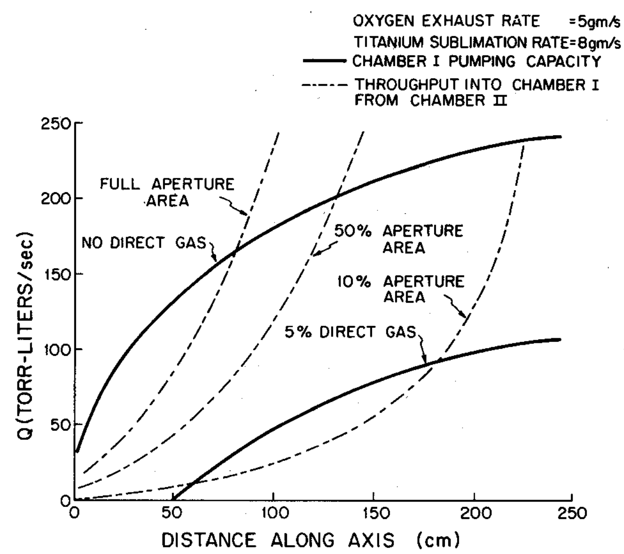


Fig. 2 Calculated performance of proposed pump with oxygen.

Titanium pumping speeds were calculated using the full surface area of the baffle and cylindrical walls only, taking into account the occupation of titanium sites on the walls by the freshly depositing titanium atoms.[14] The pressure in chamber I is then determined by 1) the direct gas flow into chamber I (including cold gas from the arcjet and plume scrape-off from the collimator), and 2) gas backstreaming into chamber I through the collimator from chamber II. The backstreaming gas depends upon the effective size of the aperture (i.e., its geometrical size and the extent to which it is plugged by the plume) and the pressure in chamber II.

The advantage of this differential pumping arrangement is that a higher pumping throughput is obtained in chamber II for fixed-wall pumping speed, since the pressure is higher there

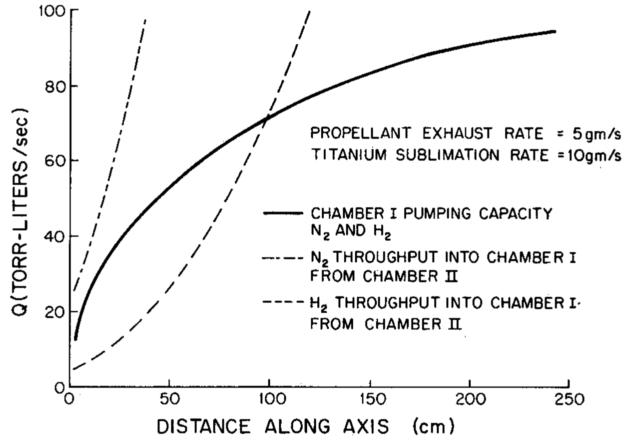


Fig. 3 Calculated performance of proposed pump with hydrogen and nitrogen.

than in chamber I. The distribution of the pumping load in the two chambers is determined by the axial position of the baffle. As the baffle is placed further downstream, the high-pressure region has less pumping area and operates at increased pressure, which drives more gas through the larger aperture (because of plume divergence). The low-pressure chamber has more area and more available pumping capacity at 10^{-4} Torr that, nonetheless, must offset the increased throughput from chamber II. The pumping capacity of chamber Q_I can be written as

$$Q_I = P_I s[A_I(z) + A_B(z)] \qquad (1)$$

where P_I is 10^{-4} Torr, the pressure maintained in chamber I, $A_I(z)$ is the cylindrical wall area of the vessel, $A_B(z)$ is the baffle area, and $s = 9$ l/s/cm^2 is the pumping speed per unit area corrected for the sticking coefficient. The areas here contain the dependence on the axial coordinate z.

Similarly, the throughput from chamber II into chamber I Q_{II-I} can be written

$$Q_{II-I} = \frac{C_A Q}{sf[A_{II}(z) + A_B(z)]} \qquad (2)$$

where Q is the gas originating from the MPD thruster (assumed to be 2700 Torr-l/s, C_A is the conductance of the baffle aperture into chamber I, and f is the modification of the pumping speed due to titanium atom deposition on unoccupied titanium sites.[14] In practice, the axial position of the baffle is constrained by mechanical access, such as placement of diagnostic ports, as well as by pumping considerations. The design of the system requires two pieces of data, the gas input directly into chamber I from the arcjet and the plume divergence (which determines the maximum nonscraping aperture size). Because of the large excess capacity in chamber I, a wide range of these parameters can be accommodated. Figure 2 displays two sets of curves. Those labeled in boldface indicate the maximum pumping capacity of chamber I [Eq. (1)] as a function of axial collimator position for the extremes of 1) no direct gas, and 2) 5% direct gas (135 Torr-l/s). The dashed curves give the gas throughput in chamber I from chamber II [Eq. (2)], for an effective size of 1) 10% aperture area, 2) 50% aperture area, and 3) the full aperture size. The titanium evaporation rate in this chamber is 8.5 g/s. It can be seen that, for some configurations, the pumping is insufficient. However, for a reasonable 10% open aperture area and 5% direct gas, there is a suitable range of baffle positions.

For the case illustrated in Fig. 2, more than 95% of the total plume throughput is pumped in chamber II. If the area between the plume and the baffle is 10% of the total aperture area, then the throughput from chamber II into chamber I is 50 Torr-l/s. Since the available pumping throughput in chamber I is 220 Torr-l/s at the target pressure of 10^{-4} Torr, the backstreaming gas should be easily accommodated.

Figure 3 illustrates reduced pumping capability with hydrogen and nitrogen propellant. Only the cases of "no direct gas" from and the arcjet and "full aperture area" conductance are shown.

In chamber I, the atomic titanium deposition rate can easily be much greater than the molecular gas absorption rate. Since hydrogen's lower sticking coefficient compensates for its higher velocity, pumping speeds for molecular hydrogen and nitrogen to a room temperature wall are both approximately 3 l/s/cm^2. This is reflected in a single curve for "pumping capacity." However, in chamber II, where most of the propellant is pumped, the effective pumping speed is sensitive to the ratio of molecular gas absorption rate to titanium atomic evaporation rate. Since maximum titanium utilization for nitrogen is half that of hydrogen,[14] the pumping characteristics with hydrogen are better. In this example, nitrogen could not be pumped at 5 g/s.

It has been shown that, for a tightly focused e-beam sublimator operating at ~ 0.05 g/s, the titanium plume is emitted with a cosine distribution.[17] If the shape is characteristic of the high throughput units required, then, in the geometry of Fig. 1, mean free paths for mutual scattering of the oxygen and titanium plumes are much less (~ 20 cm) than dimensions of the vacuum vessel. Practically, it may prove necessary to mask the titanium plume or shield it from the oxygen plume to prevent scattering of oxygen into chamber I with its accompanying gas load.

Although this design has focused on the desired goal of 5 g/s propellant throughput, with lower throughputs the facility can run for longer times.

If the throughput requirements were dropped to 1 g/s, the test facility could be operated in oxygen for up to 15 h without reloading.

Conclusion

A pumping system is designed for testing MPD arc thrusters. It utilizes multiple chambers, differentially pumped by titanium gettering of oxygen, nitrogen, and hydrogen. The design and pumping characteristics are based upon the results of a similar system already operating successfully and has the advantages of an existing, proven technology.

The pump is capable of 5 g/s of oxygen for each commercial 100 g/s titanium evaporator and can be operated for hour-like time scales.

Acknowledgments

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