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EVALUATION OF A STEADY STATE MPD THRUSTER TEST FACILITY*

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C. B. Reed, L. W. Carlson, H. Herman, E. D. Doss
Argonne National Laboratory, Argonne, Illinois
and

DE86 003051

O. Kilgore
USAF Rocket Propulsion Laboratory
Edwards Air Force Base, California

Abstract

The successful development of multimegawatt MPD thrusters depends, to a great extent, on testing them under steady state high altitude space conditions. Steady state testing is required to provide thermal characteristics, life cycle, erosion, and other essential data. The major technical obstacle for ground testing of MPD thrusters in a space simulation facility is the inability of state-of-the-art vacuum systems to handle the tremendous pumping speeds required for multimegawatt MPD thrusters. This is true for other types of electric propulsion devices as well. This paper discusses the results of the first phase of an evaluation of steady state MPD thruster test facilities. The first phase addresses the conceptual design of vacuum systems required to support multimegawatt MPD thruster testing. Three advanced pumping system concepts were evaluated and are presented here.

Introduction

Multimegawatt MPD thrusters have traditionally been tested in the pulsed or quasi-steady state mode primarily due to the inability of conventional pumping systems to handle the propellant flow rates associated with thrusters of this power class. The results of studies on the effects of test chamber pressure on MPD thruster performance have been well documented. These studies show that, for valid testing of MPD thrusters, the chamber pressure must be maintained below 10^{-4} torr. To maintain this pressure with an argon propellant flow rate of several grams per second, systems with a pumping capability greater than 10^7 cfm would be required. If an oil diffusion pump system were used, more than one hundred large diffusion pumps would be required in addition to backing pumps. Clearly, this is impractical. Therefore, the vacuum system has been identified as the most critical component in the design of a multimegawatt MPD test facility.

The requirements for the present vacuum system are as follows: It must be capable of maintaining a test chamber pressure below 10^{-4} torr with a propellant mass flow rate of 6 grams/sec of argon. The system must be capable of operating for a sufficiently long period of time to establish equilibrium for steady-state MPD thruster operation. It must be able to operate with the tremendous heat load generated by the multimegawatt thruster. The cost of

constructing and operating the facility must be at least as economical as space testing.

Advantages and disadvantages of space testing versus ground testing are shown in Table 1. Ground testing is preferable for thruster development. By testing in space, the vacuum obstacle is overcome but the requirement for continuous high levels of electric power cannot be met, at least not in the near term. A development program for high thrust electric propulsion will probably be conducted at a ground test facility, but space testing will probably be used for qualification, verification, and other tests which cannot be completed at a ground test facility with a high degree of certainty.

Table 1. Advantages and Disadvantages
of Space Testing vs Ground Testing

- Space Testing Advantages:
 - Excellent vacuum capability
 - Desirable for plume and contamination studies
- Space Testing Disadvantages:
 - Expensive
 - Multimegawatt power unavailable
 - Flightweight system required
 - Complex control and data acquisition
 - Long lead times between tests
- Ground Testing Advantages:
 - Development testing is more feasible
 - Multimegawatt power is available
 - Conventional control and data acquisition
 - May accept various thrusters
 - Propellant storage and supply easily maintained
- Ground Testing Disadvantages:
 - Conventional vacuum systems inadequate

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Advanced Pumping Concepts

Three advanced pumping system concepts were developed. All three share one feature -- a gas cooling subsystem. The multimegawatts of power deposited in the propellant gas by the MPD thruster must be removed; otherwise they will be absorbed by the vacuum chamber and the pumping system components. Also, gasdynamic diffusers are employed to some extent on all three system concepts. The gas coolers and gasdynamic diffusers differ in design and are located in different places from system to system. The functions they perform are the same in all cases -- heat removal for the gas coolers and pressure recovery for the gasdynamic diffusers.

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Gas Cooling

Plasma cooling upstream of the pumping systems is required, except for the case of direct electromagnetic pumping of plasma. The plasma plume enthalpy load represents much of the power expended in the plasma jet engine. Thus, an energy rate of several megawatts is carried by the plasma in the form of ionization, kinetic, and sensible energies. Most of this enthalpy flux must be dissipated in a structure ahead of the pumping system for a number of reasons: (1) energy levels of the plasma would otherwise be too high for pumping equipment in terms of operating temperatures, (2) volume flow rate of the gas load is proportional to the sensible temperature, and (3) any cryogenic cooling system heat loads would be too high in terms of boil-off rate and refrigeration cost.

The structure which is used to cool the plasma to near-ambient sensible temperatures can also serve another useful function in acting as a gasdynamic diffuser in which some of the dynamic pressure head is recovered as static pressure head, thereby reducing the volume rate of flow which must be pumped.

At the pressure levels of interest in an operating MPD thruster vacuum system (10^{-4} torr), and for sensible temperature levels of several thousands of degrees Kelvin, the mean free path of the gas is several "tens of centimeters." Accordingly, the plasma cooling structure is conceived to be an open "egg crate" structure having square channels of approximately 30-centimeter sides and 6-meter length (see Fig. 1). An array of multiple parallel channels fills the 6-meter diameter vacuum chamber cross section. The plasma plume flows through these parallel passages coaxially to the vacuum tank axis. The approximately 3 to 5 molecular collisions with the walls inside the parallel channels during the traversing of the structure are expected to release the resident enthalpy of ionization and sensible heat "fairly uniformly" along the structure. Heat fluxes at the leading edges of the surfaces are expected to be higher than surface fluxes. Water cooling is provided along the leading edges of the flow channels and at the corners of the channels. Thus, the higher leading edge heating rates are accommodated directly. The lower surface heating rates are accommodated by "fin conduction" from the surfaces to the adjacent corner cooling passages. The surfaces are slotted at regular axial intervals in the direction perpendicular to the flow to allow for local accommodation of differential thermal expansion. The axially situated cooling tubes are soldered to the fin surfaces and are used for fastening the entire structure together by banding adjacent tubes together with mechanical "ties" passed through the slots in the surfaces.

Gasdynamic Diffusers

Present knowledge of plasma dynamic velocity diffusion and pressure recovery from hypersonic flows is limited, especially in the free molecular and transition regions of gas dynamics. Consequently, the amount of pressure rise which can be expected in a constant area channel is not known. The "rule of thumb" which

is used in low density neutral gas continuum flows is that a straight duct can recover 80% of the pressure ratio of a normal shock for the corresponding inlet Mach number. If the plasma plume of the MPD thruster of the present study is expanded to fill the entire cross section of the vacuum tank (6-meter diameter) at a static pressure of 10^{-4} torr, the dynamic pressure head is over 10^{-2} torr and the shock pressure ratio predicted for an ideal gas is approximately 80. The maximum expected pressure gain in the cooled diffuser structure, ignoring plasma cooling effects (which also should result in static pressure gain), approaches 10^{-2} torr. The present vacuum facility pumping systems have been designed to operate with diffuser pressure ratio gain of 3 to 5. Consequently, the designs presented here are believed to be conservative for expected gas flow rates, thruster power levels, and plasma velocities.

Although the use of diffusers or stream-tubes is not new, it has never been applied to MPD thruster testing. The design of diffusers for chemical rockets is based on empirical data as will be the design of diffusers for MPD thrusters. An MPD thruster diffuser will have to handle a much more hostile gas than found in chemical rocket exhausts: higher temperatures, higher velocities, and plasma-rarefied. Because of the unique characteristics of this exhaust, the diffuser will have to be developed by parametric testing to determine diffuser performance and its effect on thruster operation. Although the gasdynamic diffuser is economical and would probably aid in maintaining the desired vacuum, it may not permit plume studies.

Argon Prebooster/Oil Vapor Booster

One of the possible means to pump approximately six grams per second of argon gas from the vacuum chamber at a characteristic static pressure of 10^{-4} torr is to use staged ejector type pumps in series downstream of the initial hypersonic diffuser pressure-recovery and cooling device previously described. Commercially available multi-stage oil-vapor booster pumps can handle approximately 20,000 liters per second at pressure levels down to 10^{-4} torr. They act much like standard vacuum diffusion pumps in terms of their operating characteristics but can handle larger gas loads than diffusion pumps due to the higher pressure of their oil jets. For the vacuum system under consideration, using oil vapor booster pumps alone would require 720 units to achieve operating pressures near 10^{-4} torr, which is entirely impractical. A means to increase the pressure of the argon gas by almost two orders of magnitude and to reduce the number of oil-vapor booster pumps to a reasonable value (12) is required.

Prebooster gas ejector pumps using recirculated argon for the driver gas were designed based upon theoretical continuum flow mechanics with appropriate "correction factors" applied to the mass flow and pressure ratios to yield realistic values. Three additional stages of argon-driven ejector pumps are required to raise the MPD thruster gas load from an assumed pressure of 3×10^{-2} torr and temperature of 300 R.

At these latter conditions, the largest available oil-vapor booster pumps can raise the total argon throughput (including the prebooster driver argon flow) to approximately 2 torr at 540 R. Any number of conventional mechanical vacuum pump systems can then boost the argon gas load to atmospheric pressure (or higher pressures if it should be desired to recirculate the argon through a purification system for reuse in the magnetoplasmadynamic thruster engine). The argon which is recirculated to drive the prebooster ejectors is only pressurized to approximately 50 torr.

The first stage of each of twelve argon prebooster ejectors is configured in an annular arrangement to fit within the vacuum system space. A system concept showing five of the six pumps on one side of the tank is shown in Fig. 2. Inlet diameter is constrained by the size of the holes which can be provided in the walls of the vacuum tank, and by space available in the building housing the vacuum system. The second and third stages of the argon prebooster ejectors are coaxial in configuration to optimize pumping speed. A detail of this argon prebooster configuration is shown in Fig. 3. It is estimated from available design references that the annular first stage has only 70% of the pressure gain of an equivalent axial stage.

Table 2 summarizes the results of an example calculation of the operating state points of such a system. These are not optimized state points but rather first iteration feasibility results.

Continuous Cryogenic Pumping System

An approximately 18-ft-diameter panel at a temperature in the range of 20-30 K will be capable of maintaining the desired 1×10^{-4} torr pressure at high argon flow rates (6 g/sec). Condensate (ice) buildup will, however, very quickly reduce pumping capacity unless there is some means to regenerate the pump, or remove the ice by other means. Regeneration when continuous long-term operation is required is not possible with the given configuration, but removal of the ice by scraping is.

Two scraping concepts are feasible; one employs a mechanical scraper, the other a "thermal" scraper. There are good grounds to

believe that the condensate will be similar to snow in consistency, so that scraping it from the cryopanel should not be difficult. If it cannot for some reason be scraped mechanically, an alternative approach is to selectively boil off condensed argon in a controlled manner, without loss of pumping speed. The two concepts are as follows:

Mechanical Scraper. The main pump features are shown in Fig. 4. The cryopanel temperature is held at 30 K or less by refrigerated gaseous helium. (The vapor pressure of argon at this temperature is in the mid 10^{-7} torr region.) A high transmission baffle cooled to approximately 80 K shields the cryopanel main pumping surface; radiation shielding at approximately 80 K surrounds the remaining low temperature surfaces. The complete assembly is held by low heat leak supports.

A sharp blade whose length is roughly the same as the cryopanel radius is connected to a central shaft supported by bearings. The shaft penetrates the vacuum chamber wall via rotary seal and is driven at low speed by an electric motor. The slowly rotating blade scrapes the condensed argon from the cryopanel where it falls by gravity through a chute arrangement into a cryostat appended to the vacuum chamber. Blade speed is matched to gas flow to ensure equilibrium between ice deposition and removal.

The cryostat inner container is maintained at 30 K so that the collected solid argon remains in that state. When full, a cryogenic gate valve at the bottom of the cryostat is opened and the solids fall into a chamber, which is later warmed. Then the gate valve is closed and ready to collect ice particles again. The chamber is warmed, the argon gasified and removed at relatively high pressure (~ 10 torr) by means of a Roots blower/mechanical pump combination.

"Thermal" Scraper. The thermal scraper configuration shown in Fig. 5 is similar to that of the mechanical scraper, with the following exceptions:

- (a) The cryopanel surfaced in finned.
- (b) The scraper does not contact the cryopanel surface (except for the lip seal).

Table 2. Argon Prebooster Enhanced Vacuum System Stage Conditions
(per port)

Item	1	2	3	OVB	Roots Blower
Driver Press (torr)	0.3	3.0	8.4	-	-
Throat Dia/Width (in.)	0.065	2.55	2.0	-	-
Exit Dia/Width (in.)	3.1	24.0	11.0	-	-
Inlet Press (torr)	3×10^{-4}	1.5×10^{-3}	8.4×10^{-3}	4.5×10^{-2}	2.0
Outlet Press (torr)	1.5×10^{-3}	8.4×10^{-3}	4.6×10^{-2}	2.0	50.0
Inlet Temperature ($^{\circ}$ R)	300	142	92	82	Amb.
Outlet Temperature ($^{\circ}$ R)	142	92	82	Amb.	Amb.
Inlet Vol. Rate (ft^3/sec)	15,300	4,100	1,200	400	60
Outlet Vol. Rate (ft^3/sec)	4,100	1,200	400	60	2

- (c) gasified argon is removed directly from the scraper through a fixed hollow shaft.

A cross section of the scraper and cryopanel is shown in Fig. 6. The location is denoted by the arrows "A-A" in Fig. 5. The scraper comprises a semicircular section closed-end duct with a cartridge heater positioned as shown. Power (up to 1 kW) is provided to the heater so that heat is transmitted to the finned surface of the cryopanel to boil off the condensed argon without causing any significant temperature increase in the cryopanel itself. The honeycomb cell wall is designed to conduct just the amount of heat needed.

The scraper rotates around a fixed duct from which high pressure (~10 torr) argon is continuously removed by a Roots blower/mechanical pump combination. A motor outside the vacuum chamber drives the scraper through a rotary vacuum seal. Slip rings attached to the drive shaft allow power to be supplied to the heater. A lip seal attached to the sides of the duct prevents significant gas leakage back to the cryopanel.

Axisymmetric Linear Induction Plasma Pump (ALIPP)

This concept is based on using an electromagnetic (EM) pump to raise the pressure of the plasma in the vacuum chamber. (EM pumps are commonplace in liquid metal pumping systems.) The pumped fluid is the ionized propellant gas of the MPD thruster.

The function of the EM pump is to lower the velocity while raising the pressure of the MPD plume from roughly Mach 6 and 10^{-4} torr to a subsonic velocity and a pressure that matches the downstream pumping system. However, high Mach number and low pressure conditions are maintained at the thruster end of the chamber while the subsonic, high pressure condition (10^{-1} to 1 torr) prevails at the far downstream end where a conventional mechanical pumping system can handle the gas load.

The physical layout of an axisymmetric linear induction plasma pump (ALIPP) is shown in Fig. 7. Reference 1 proposes a similar device for plasma acceleration and briefly discusses the principle of operation where a traveling wave is applied to the plasma. In Ref. 2, a one-dimensional analytical model was developed for performance predictions of a traveling-wave EM pump and some results were presented. In Ref. 3, experimental results were presented showing that a similar device operating as a plasma accelerator could be operated at roughly 50% efficiency. In the traveling wave pump, electrodes do not contact the plasma, which is a big advantage because electrodes are usually subject to rapid erosion at the current densities considered for plasma propulsion.

In general, such a device can be operated either as an accelerator or as a pump, depending on the particular application and the boundary conditions downstream of the flow. In the accelerator mode, the device accelerates the plasma to supersonic velocities, whereas in the

pump mode, the flow is decelerated to possibly subsonic velocities depending on the downstream pressure. According to Ref. 4, in the pump mode, the enthalpy, the pressure, and the gas density all rise along the direction of the flow while the velocity falls.

Reference 5 gives a rather detailed analytical treatment of an annular linear induction pump for liquid metal applications. Referring to Fig. 8, the operating principle of the ALIPP can be understood as follows. A series of coils are placed inside the vacuum chamber far enough downstream of the thruster so as not to disturb the exhaust plume. A 3-phase AC current excites the coils and generates a traveling magnetic field which propagates along the part of the chamber which contains the coils. The shape of the B-field lines at one instant in time is shown in the figure. Both radial and axial components of the magnetic field exist at most points inside the coils. Because of the axisymmetry, there is no azimuthal magnetic field. Through Maxwell's equations in the following form,

$$\frac{\partial B}{\partial t} = -\nabla \times E,$$

the time varying B-field induces azimuthal current flow in the ionized plume of the MPD thruster. This current interacts with the axial component of the B-field to produce radial forces on the plume. The induced current also interacts with the radial component of the traveling field to produce the desired axial pumping force on the plume.

The axial pumping force per unit volume is proportional to the plasma conductivity, the strength of the radial component of the B-field, and the difference between the plasma velocity, V_p , and the wave velocity, V_w , of the traveling field as follows:

$$F \sim \sigma (V_w - V_p) B_r^2.$$

If the traveling magnetic wave is moving faster than the plasma, the pumping force will be in the direction of motion of the plasma. If the downstream pressure is low, the plasma will accelerate and can reach supersonic velocities; in this case the device acts as an accelerator. On the other hand, if the downstream pressure is higher than upstream, the device will act as an EM pump, thus slowing the gas while increasing its pressure, which is the subject of our application.

A very crude estimate of the performance of this device shows that, for a radial component of the magnetic field, B_r , of 1000 gauss (0.1 T), a plasma conductivity of 10 S/m (corresponding to argon temperature $T = 3800$ K and pressure $P = 10^{-4}$ torr, see Fig. 9) and a relative velocity of 25,000 m/s, a pressure gradient of 2500 N/m^3 (~18.8 torr/m) is possible. Hence, it seems quite possible to maintain an overall pressure distribution in the vacuum chamber having 10^{-4} torr at the MPD thruster exhaust and 10^{-1} to 1 torr at the outlet of the ALIPP.

However, for this device to work as intended, the applied traveling B-field must

penetrate the plume to apply the Lorentz ($\mathbf{J} \times \mathbf{B}$) body force on the ionized gas. This can occur if the magnetic Reynolds number is small or moderate. In this case, the applied traveling magnetic field will penetrate the plasma to a distance referred to as the skin depth, δ . The skin depth is inversely proportional to the product of the plasma electrical conductivity, σ , the plasma permeability, μ , and frequency of the traveling wave, ω . The skin depth, δ , is given by the following relation:

$$\delta = (2/\sigma\omega\mu)^{1/2}$$

where $\omega = 2\pi\nu$.

Figure 10 presents the variation of the skin depth as a function of argon temperature (conductivity) with the AC frequency of the traveling field as a parameter. There is flexibility for selecting feasible frequencies and skin depths.

According to the behavior described above for the device, the overall flow field will appear as follows. The plume entering the ALIPP will be at Mach 6 or so and a pressure of 10^{-4} torr. The plume will be decelerated by the ALIPP to roughly Mach 1 or lower. In this region of the ALIPP, the electromagnetic forces on the plume will be pushing the plume forward while increasing its density and pressure. In other words, the ALIPP will act on the plume in a more classical pumping fashion; it will add energy to the flow by further increasing the pressure and density while reducing the velocity accordingly. The traveling wave speed is set by the requirement that the ALIPP exhaust velocity be subsonic at the discharge pressure set by the backing system (roughly 10^{-1} to 1 torr). The remaining ALIPP parameters, such as the traveling field wave length, the field strength, and the overall coil structure length, are set by optimally matching the ALIPP discharge pressure to the backing system pressure.

It is anticipated that adequate electrical conductivity will remain in the MPD thruster plume to satisfy feasibility requirements. If further work shows this to be questionable, a reduced conductivity can be compensated for by either increasing the magnitude of the traveling B-field or by re-ionizing the plume. A number of means can be employed to re-ionize the plume, such as microwave heating, electron cyclotron or ion cyclotron resonance heating, electrothermal heating by a separate E- or B-field system,⁶ or perhaps by re-ionization of the gas along the first few coils of the ALIPP itself.³

A final point should be mentioned. The previous discussion has been developed under the assumption that the plasma being pumped by the ALIPP is a relatively dense, collision dominated, continuum gas. This is most probably true in the core of the plume, but near its edges and outside the plume, the gas entering the ALIPP will be at an equilibrium pressure of roughly 10^{-4} torr. In this annular region around the MPD plume, free molecular flow prevails and the mean free path is roughly 50 cm.⁷ However, ions and electrons will still be pumped by the traveling B-field as they spiral around the field lines at their respective Larmor radii. Further investigation of this point is needed.

Conclusion

Three advanced vacuum pumping system concepts, suitable for use in steady-state MPD thruster test facilities, have been identified. Preliminary engineering estimates have established concept feasibility in all three cases. Cost estimates and risk assessments can be prepared to select a primary candidate for further R&D efforts.

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FIGURE 1. MPD THRUSTER VACUUM SYSTEM WITH INTERNAL COOLING DIFFUSER

FIGURE 2. ARGON PREBOOSTER VACUUM CHAMBER CONCEPT

FIGURE 3. ARGON PREBOOSTER CONCEPT DETAIL

FIGURE 4. CONTINUOUS CRYOGENIC/MECHANICAL SCRAPER PUMPING CONCEPT

FIGURE 5. CONTINUOUS CRYOGENIC/THERMAL SCRAPER PUMPING CONCEPT

SECTION A - A

FIGURE 6. THERMAL SCRAPER CONCEPT

FIGURE 7. AXISYMMETRIC LINEAR INDUCTION PLASMA PUMP (ALIPP)

FIGURE 8. PHYSICS OF AXISYMMETRIC LINEAR INDUCTION PLASMA PUMP (ALIPP)

FIGURE 9. CONDUCTIVITY OF ARGON

FIGURE 10. ALIPP SKIN DEPTH

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