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Exploratory Tests on a Downstream-Cathode MPD Thruster

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Substantial improvement in the thrust performance of a low-power MPD arc thruster has been achieved in the specific impulse range of 600 to 2100 sec. The thruster tested utilizes a cathode positioned in the exhaust beam, downstream of the anode, as opposed to the conventional position upstream of the anode. Xenon is the propellant used, and testing is conducted in a background pressure of 1.6×10^{-5} torr. Operation achieved in the above specific impulse range is at thrust levels from 6 to 16 mN, power levels of 180 to 720 w, and thrust efficiencies of 13 to 24%.

Nomenclature

g = gravitational constant
I_{sp} = specific impulse
$\dot{m}$ = propellant mass flow rate
P_D = power supplied to discharge
T = thrust
η_T = thrust efficiency

Introduction

A SIMPLE, low-power magnetoplasmadynamic (MPD) arc thruster is attractive for such auxiliary propulsion applications as satellite station keeping and attitude control.[1] An electrical discharge is maintained in an axial magnetic field between a cylindrical anode and a cathode centered on the anode axis. The cathode of a conventional MPD arc thruster is located upstream of the anode-discharge region (Fig. 1). Such a thruster performs best (T/P_D vs I_{sp}) when operating on xenon propellant.[2]

Theory places a 40% to 70% limit on thrust efficiency η_T for specific impulses in the range of 700 to 2000 sec (when xenon propellant is used).[3] Severe loss to the thruster backplate appears to be a possible source of additional energy loss in many existing thrusters. This backplate loss may explain, in large part, why it is impossible to achieve η_T's even one-half of those predicted by the theory.

Data are presented for a new thruster (Figs. 2 and 3) in which four major modifications have been made: 1) the cathode is in the exhaust, downstream of the anode, electromagnets and propellant injection points; 2) an orifice plate is added to the tip of the hollow cathode; 3) magnetic pole pieces are added to the thruster anode chamber region; and 4) the magnetic field is produced by edgewound electromagnets.

Placing the thruster cathode downstream of the anode eliminates an impressed electrostatic field which tends to

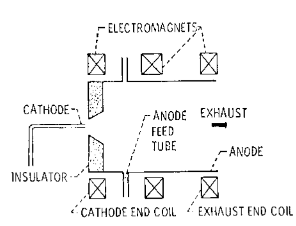

Fig. 1 Schematic of the low-power MPD arc thruster (conventional arrangement) investigated by Johansen et al. (Ref. 2).

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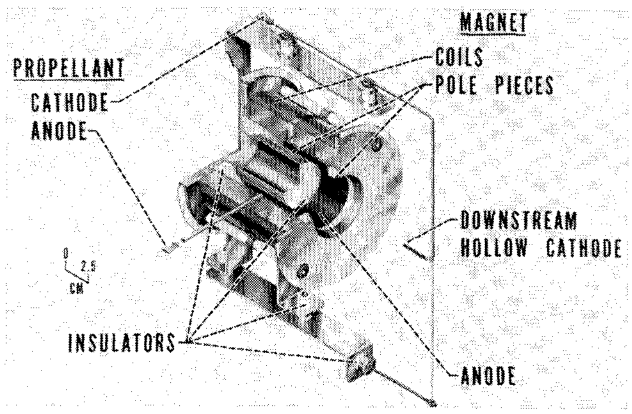


Fig. 2 The downstream-cathode MPD thruster.

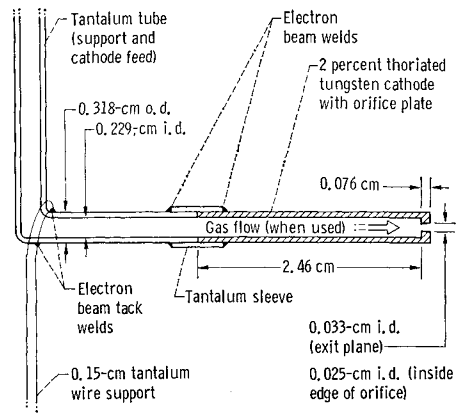


Fig. 3 Cross-sectioned schematic of the 2% thoriated tungsten hollow cathode; support structure and feed tube also shown.

accelerate ions toward the backplate causing backplate loss and replaces it with an impressed electrostatic field which tends to accelerate ions out of the exhaust. Bowditch[4] has shown that ion acceleration in the low-power MPD arc thruster is through an electrostatic field established in the exhaust by the hot electrons of the plasma as the electrons expand in the magnetic field (nozzle). The position in Bowditch's exhaust where the plasma potential is identical to the cathode potential was selected as the most reasonable place for positioning the downstream cathode tip (without perturbing the potential distribution established in the exhaust by the electron expansion process).

Hollow cathode studies by the author in the conventional low-power MPD arc thruster have shown that the addition of an orifice plate to the tip of the hollow cathode tends to make the discharge more stable. For this reason it was decided to also use this type of cathode as the downstream cathode.

The insertion of pole pieces in the anode chamber was also prompted by a desire to eliminate backplate loss. The field established by the magnets of the conventional thruster diverges away from the thruster axis at the backplate. Hence the magnetic expansion process that Bowditch found important in the exhaust can also be operative in accelerating ions into the backplate. The pole pieces permit shaping of the field such that it converges at the backplate (e.g., acting like a magnetic mirror and inhibiting magnetic expansion) and diverges in the exhaust region. Figure 4 is a map (in iron filings) showing the divergence imparted to the magnetic field.

Johansen and Palmer[5] have shown that an edgewound aluminum magnet is attractive for use in producing the magnetic field of an MPD arc thruster. Two such magnets were used on the thruster tested in an attempt to gain experience in fabricating such magnets and to check the theoretical calculations of Johansen and Palmer.

Apparatus

The xenon propellant flow for most of the testing was split, with 80% or more entering the anode via two feed tubes placed 180° apart and set perpendicular to the anode surface and the remainder entering the thruster via the downstream hollow cathode. Anode dimensions, anode feed tube location and propellant flow rates are almost identical to those used for the conventional MPD thruster in Ref. 2. The thruster tested weighs 2.88 kg (6.4 lb). As will be shown later, the upstream magnet is not needed, and when it is removed, the thruster weighs 2.23 kg (4.9 lb).

Figure 3 shows the hollow cathode and support structure. The straight section of 2% thoriated tungsten tubing and the orifice plate are electric-discharge-machined from a single piece of rod. The upper portion of the cathode support is a hollow tantalum tube that also supplies any cathode propellant used. Both the feed tube and the bottom tantalum support wire are at cathode potential and are alined vertically to keep electrical symmetry. During operation, ion bombardment of the orifice plate keeps the cathode tip hot enough ($\sim$1850°K) to maintain the discharge. If cathode propellant is used, it flows from the orifice in the cathode tip in an upstream direction relative to the exhaust. Cathode propellant is always used for starting the discharge. The discharge current attaches either at the inside diameter of the orifice hole or slightly behind it, inside the hollow tube, and remains even when cathode flow is subsequently removed.

The edgewound magnets are built by lap-welding split aluminum washers to form a continuous helix. Each washer-shaped turn is 0.010 cm (0.004 in.) wide, has an i.d. of 7.3 cm and an o.d. of 10.9 cm. To mate adjoining turns, the radial cuts of neighboring turns are overlapped 0.3 cm and a resistance weld made along the length of the seam. (The seams are staggered 30° to optimize the coil packing fraction.) The assembled magnets are then anodized to insulate turns. Each magnet, with its 360 turns, produces a field of 0.02 tesla at its center for a current of 4 amp and a voltage of 12 v. Magnet design and operation are almost identical to that shown for the 3.75-cm-radius magnet in Table 1 of Johansen and Palmer,[5] except that the magnet has a packing fraction of only 0.63.

The two magnetic pole pieces for the MPD thruster tested (Fig. 2) are made of 1020 low carbon steel, flame sprayed with

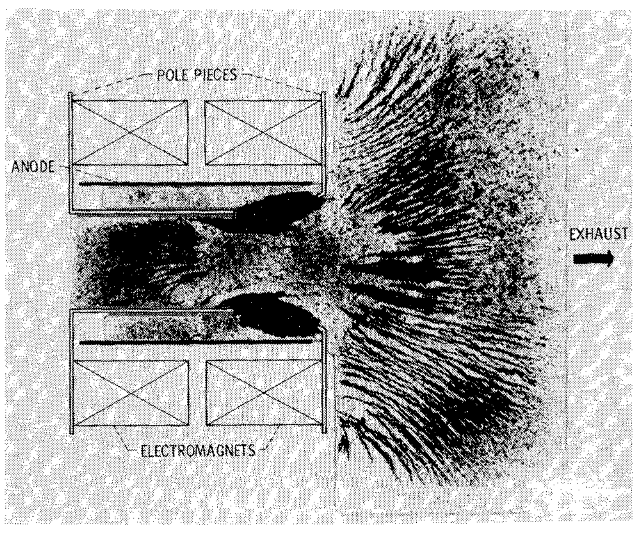


Fig. 4 Magnetic field map of downstream-cathode MPD thruster (4 amp exhaust-end coil).

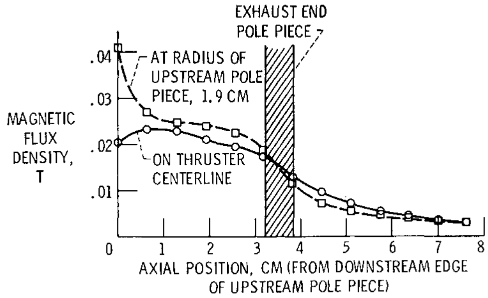


Fig. 5 Plot of axial component of magnetic flux density vs axial position from downstream edge of upstream pole piece; exhaust-end magnet 4.0 amp (d.c.) and upstream magnet disconnected.

alumina to a thickness of ~0.035 cm to insulate them from the plasma. The upstream pole piece is made of a 0.075-cm-thick washer disk with an o.d. of 13.2 cm and an i.d. of 3.96 cm, welded to a thin-wall (0.075 cm) cylinder with an o.d. of 3.96 cm and a length of 6.58 cm. When in the thruster, the cylindrical part of this pole piece extends 5.95 cm into the anode chamber. A boron nitride insulating cap over the downstream end of the cylinder inhibits particle diffusion and/or acceleration into the inside of the pole piece.

The exhaust-end pole piece is basically a thin washer-type disk with an o.d. of 13.2 cm, and a bevel imparted to the edge of the i.d., which begins at 5.97 cm diameter; the bevel ends at an i.d. of 5.41 cm. The beveled edge makes an angle of 24° with the thruster axis. The axial spacing from the downstream edge of the upstream pole piece to the upstream edge of the downstream piece is 3.49 cm.

Most of the data presented herein are for a direct current of 4 amp to the exhaust-end magnet and no current to the upstream magnet. Figure 5 shows the axial component of magnetic flux density for this case.

Figure 6 depicts the circuit used to supply power to the discharge. A radio frequency arc starter is used to initiate the discharge. Experiments were conducted in a 1.5-m-diam by 5.0-m-long vacuum tank. Background pressure was maintained at 1.6×10^{-5} torr or less. The thruster was mounted at one end of the tank, and the exhaust plume extended along the tank's axis.

The parallelogram-pendulum thrust stand is shown in Fig. 7. The four pendulum struts (two on each side of stand)

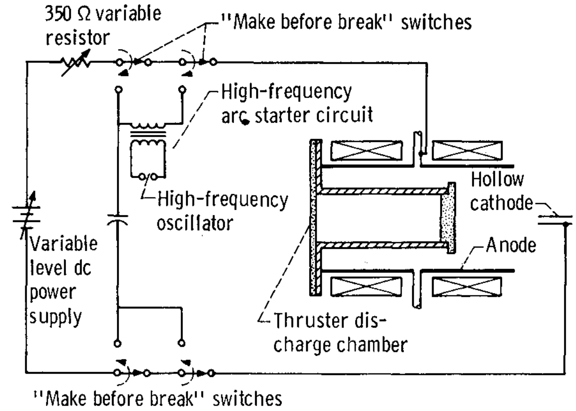


Fig. 6 Schematic of discharge power supply circuit including high-frequency arc starter (shown switched out of circuit).

are attached to the reference platform by low-friction ball bearings rated for low-vacuum use. The weighted pan used for thruster mounting is attached to the struts by similar ball bearings. (Static friction loading was less than 1.0% of the lowest thrust level measured.)

The center of gravity of the movable part of the stand is below the reference platform. The mass of the stand plus the mass of the thruster acting through this point are the restoring forces when the thruster is operating. For the thrust levels involved, the stand moves through very small angles, and deflection of the stand is linearly proportional to thrust and is sensed by a linear voltage differential transformer (LVDT). The a.c. signals of the LVDT are conditioned (demodulated) by the signal conditioner and displayed on a strip chart.

The system is calibrated by a series of three weights suspended by very thin string (of negligible weight) from a moment arm of known length ($L/2$). The weights normally hang free but can be picked up in a small pan mounted inside the vacuum tank. When picked up, each weight deflects the stand an amount equal to the deflection produced by 9.8 mN of thrust. A single counterweight, equivalent in mass to the total of the three calibration weights (and having an adjustable mount), is mounted from a moment arm at the opposite end of the stand. Its position is adjusted to mechanically zero the stand. Calibration of the stand is repeatable to within 3% of the full scale deflection of 29.4 mN.

Table 1 Typical operating parameters of downstream-cathode MPD thruster (0.78 mg/sec total flow, no cathode flow)

Discharge voltage, v	Discharge current, amp	Discharge power, w	Thrust, mN	Specific impulse, sec	Thrust efficiency, %	Cathode voltage relative to ground, v	Exhaust-end coil current, amp
82	1.37	112	2.9	370	4.7	−25.0	4
93	1.54	143	4.2	540	7.7	−19.0	4
110	1.63	179	6.0	780	12.8	−17.0	4
135	1.77	238	8.0	1040	17.2	−14.0	4
158	1.86	294	9.7	1270	20.6	−11.7	4
184	1.88	346	10.7	1390	21.1	−11.7	4
228	1.82	415	12.5	1620	24.0	−12.5	4
317	1.81	574	14.5	1880	23.4	−12.5	4
345	2.08	718	15.8	2060	22.3	−0.7	4
360	3.00	1080	16.4	2130	15.9	−22.0	4
72	1.93	139	4.2	550	8.2	−13.0	2
91	2.08	189	5.9	760	11.7	−14.0	2
107	2.23	239	7.4	960	14.4	−10.5	2
122	2.46	300	8.9	1160	16.9	−7.5	2
171	2.12	362	10.5	1370	19.6	−8.0	2
208	2.22	462	11.7	1520	19.0	−5.0	2
290	2.28	662	13.8	1800	18.5	−1.0	2
320	2.51	803	15.6	2020	19.3	−0.5	2
355	3.10	1100	14.2	1840	11.7	−69.0	2

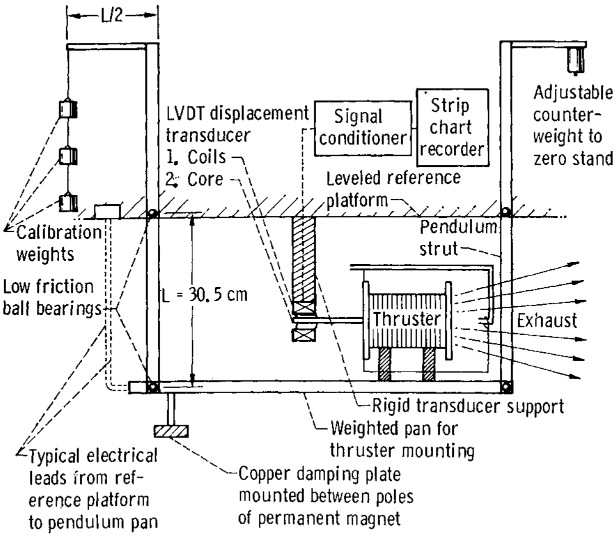


Fig. 7 Schematic of thrust stand used to measure thruster performance.

Linearity, including hysteresis due to all causes (such as the spring constants of the power leads), is also repeatable to within 3% of full scale. A copper plate suspended from the weighted thruster pan and moving between the poles of a permanent magnet provides damping for the stand under dynamic conditions.

Experimental Procedure

The thruster discharge is initiated by establishing Paschen law breakdown conditions using the arc starter; then the starter is switched out of the circuit, and the discharge supply and flow rates are adjusted to the experimental conditions desired. Propellant flow rates are set by varying the pressure upstream of fixed size "calibrated leaks." Prior to taking each thrust point, a thrust-stand calibration is taken by picking up one of the calibration weights and noting the net displacement as recorded on the strip chart. Also the thruster discharge is turned off (after noting the thrust displacement) to determine the exact zero of the stand. Measurements are made of net thrust-stand deflection, discharge current, discharge voltage, magnet current, magnet voltage, tank pressure, and $\dot{m}$, and these parameters are used to calculate I_{sp} and η_T:

$$I_{sp} = T/\dot{m}g \qquad \eta_T = T^2/2\dot{m}P_D \tag{1}$$

The thrust efficiency η_T does not include magnet power.

Each thrust point taken was also checked with the thrust stand locked down so that no deflection could occur. The maximim signal registered under this condition was well under 0.5% of reading with stand unlocked.

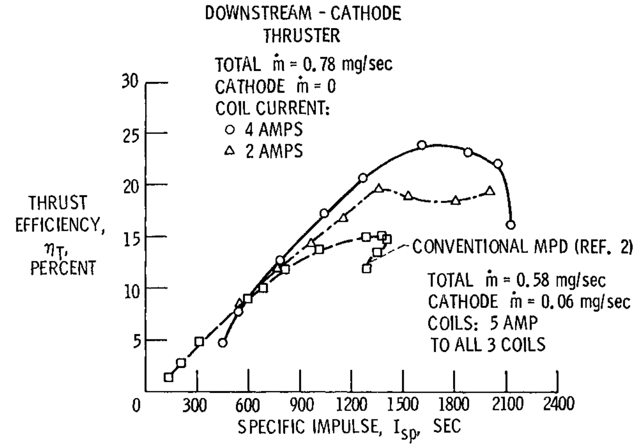


Fig. 8 Specific impulse (I_{sp}) vs thrust efficiency (η_T).

Results and Discussion

At the outset, a rapid qualitative study of thrust variations with wide variations in other parameters was conducted for the downstream-cathode MPD thruster. This was done merely by observing trends on the thrust-stand strip chart. Quantative data were then taken at parameter combinations that appeared near optimum (highest η_T at attractive values of I_{sp}) from this qualitative survey.

Qualitatively the following were examined over a power range up to 1kw: 1) optimum shape of the magnetic field, 2) optimum field strength, and 3) performance vs $\dot{m}$ for various cathode flows. The results of these qualitative tests indicated that

a) The optimum magnetic field shape was obtained using only the downstream (exhaust-end) coil.

b) For best performance a current of ~4 amp (d.c.) was needed in this downstream coil; somewhat higher currents (e.g., 6 and 8 amp) neither helped nor hurt performance.

c) The performance improves at all I_{sp}'s up to 2000 sec with increasing $\dot{m}$ up to $\dot{m} \simeq 0.8$ mg/sec.

d) The best performance occurs at zero cathode flow.

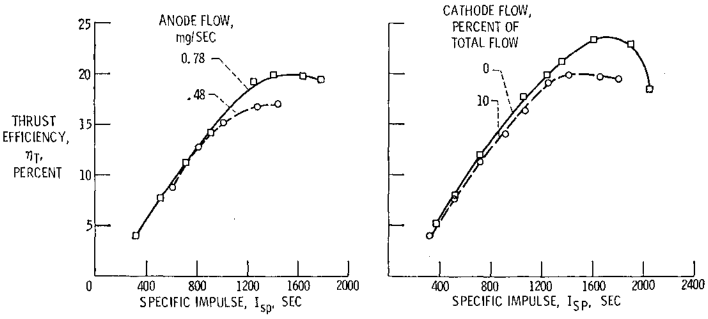
e) The performance of this thruster is substantially superior to the best previous conventional low-power MPD arc thrusters.

Figure 8 compares the best set (coil current = 4 amp) of η_T vs I_{sp} data (solid curve–see Table 1 for the operating conditions) with the best data for the conventional MPD thruster [obtained by replotting from Fig. 18 on Ref. 2 using $\eta_T = (g/2)(I_{sp})(T/P_D)$]. Clearly the downstream-cathode thruster is superior in the I_{sp} range of 600 sec to 2100 sec, the range most attractive for satellite station-keeping and attitude control.

Performance vs Magnetic Field

Any use of the upstream magnet, hurts thrust; this was verified for a number of data points. Hence the remaining

Fig. 9 Specific impulse (I_{sp}) vs thrust efficiency (η_T): a) anode flow variation with cathode flow fixed at 0.09 mg/sec and magnet coil fixed at 4 amp; b) cathode flow variation with total flow fixed at 0.87 mg/sec and magnet coil fixed at 4 amp.



(A) ANODE FLOW VARIATION WITH CATHODE FLOW FIXED AT 0.09 MG/SEC AND MAGNET COIL FIXED AT 4 AMPS.

(B) CATHODE FLOW VARIATION WITH TOTAL FLOW FIXED AT 0.87 MG/SEC AND MAGNET COIL FIXED AT 4 AMPS.

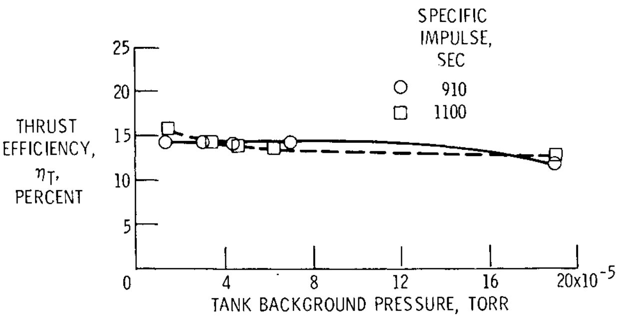


Fig. 10 Variation of thruster efficiency as a function of background pressure at two different operating points; thruster mass flow 0.78 mg/sec, no cathode flow, 4 amp downstream magnet coil.

magnetic field studies were restricted to varying magnetic field strength by varying the current of only the exhaust-end coil. At no magnetic field, η_T is well under 1/10th of 1.0%. As the magnetic field of the downstream coil is increased, the amount of thrust generated is negligible until the coil current is about 2 amp. As the current is increased to 4 amp the performance improves, and the impedance of the discharge increases. Further increase to 8 amp does not improve performance or appreciably change the discharge impedance. Figure 8 (see also Table 1) compares the 2 amp and 4 amp field conditions of the downstream-cathode MPD thruster for a total flow of 0.78 mg/sec and no cathode flow. These flow conditions were found to be near optimum.

Performance vs Mass Flow

At the outset, thruster operation was studied with flow rates almost identical to those investigated in Ref. 2 for the conventional MPD thruster. Flow was split with 0 to 20% to the cathode and the remainder to the anode. At total flows appreciably below 0.57 mg/sec, optimum for the conventional MPD thruster, operation was very unstable. Light from the exhaust plume was pulsing and the discharge terminated quite frequently. It was impossible to take thrust readings. As flow was increased stable operation was finally achieved at 0.57 mg/sec (0.48 mg/sec to anode and 0.09 mg/sec to cathode).

Figure 9a shows that with the cathode flow fixed at 0.09 mg/sec, η_T is improved (in the I_{sp} range of 800 sec to 1800 sec) as the anode flow rate is increased from 0.48 mg/sec to 0.78 mg/sec, but a further increase did not improve performance further. At flows above 1.5 mg/sec, η_T deteriorates drastically (down to 1% or 2%) and I_{sp} is low. For the operation shown in Fig. 9a, the electrical discharge is characterized by a positive resistance. At the higher flows at which η_T deteriorates, the discharge behaves more like an arc, operating at a constant voltage near 50 v with currents from 3 to 6 amp.

Figure 9b shows that η_T is improved (in the I_{sp} range 800–2000 sec) by not using cathode flow. For cathode flows at 20% of total flow, the discharge drops into the low-voltage arc type mode, characterized again by badly deteriorated η_T. Thrust efficiencies at other values of total mass flow with 10% cathode flow and with no cathode flow were spot checked. The no-cathode-flow condition indeed corresponds to the higher η_T.

Background Pressure Tests

Entrainment of tank background gas in the MPD thruster discharge could introduce error in the total mass flow and hence in η_T. To explore this problem, the tank background pressure was intentionally raised above 1.6×10^{-5} by bleeding xenon gas into the tank. Figure 10 shows that for two operating conditions η_T has a very slight downward trend as the background pressure is raised by an order of magnitude. Similar trends were obtained for the other I_{sp}'s. Thus, at the operating pressures of the tank, thruster performance is essentially independent of facility pressure. If anything, performance measurements may be slightly pessimistic compared to performance attainable in space.

Concluding Remarks

Substantial improvement in the thrust performance of a low-power MPD arc thruster can be achieved when the conventional thruster is modified in the following four ways: 1) the cathode is placed downstream of the anode; 2) an orifice plate is added to the tip of the hollow cathode; 3) magnetic pole pieces are added to the thruster anode chamber; and 4) a single edgewound electromagnet is used.

No positive proof has been rendered as to the individual contributions of these four changes. Since the field developed by the edgewound magnet is quite close to that developed by the three coils of the conventional MPD thruster, it is most unlikely as a source of the improvement. The exact influences of the addition of pole pieces to the anode chamber and of the orifice plate to the hollow cathode are unknown and require additional investigations. The characteristics of a similar discharge have been found to be quite sensitive to cathode geometry,[6] in particular to the orifice plate geometry.

It can be postulated that the downstream placement of the cathode is most responsible for the thrust efficiency improvement, for with this placement, the impressed electric field between cathode and anode is accelerating ions out of the exhaust instead of into the backplate region.

It is interesting to compare this new thruster configuration to other type plasma thrusters. For example, the Hall Current ion accelerator,[7] which makes use of a radial magnetic field to provide acceleration, has a downstream cathode in the electrical discharge chamber. So in a sense, the low-power MPD thruster with a down-stream-cathode is a hybrid of the conventional MPD thruster and the Hall current ion accelerator.

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