Performance of Quasi-Steady MPD Thrusters at High Powers

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Theme

THE familiar axisymmetric MPD thruster is considered with a conical tungsten tip cathode, ($\frac{1}{2}$, $\frac{3}{4}$, and $\frac{5}{4}$ in. diam), and a copper plate anode-orifice, (2, 3, and 4 in. diam). The performance of such thrusters is investigated, with millisecond pulses, over a wide range of experimental conditions. The five noble gases are used as propellants, at flow rates in the range 0.1 to 100 g-sec^{-1}. MPD currents 5 to 50 ka are employed and the corresponding input powers are in the range 0.1 to 10 Mw. Thrust is determined from impulse measurements with well-known current waveforms, while instantaneous measurements are made for all other variables: $\dot{m}$, J, and V, flow rate, current and voltage. A detailed analysis of the experimental results shows that the MPD performance is limited by a critical value of $(J^2/\dot{m})$, which depends only on MPD geometry and on propellant properties. MPD operation, beyond the critical point, becomes increasingly objectionable on account of instabilities, sharp rise of the voltage, erosion and participation of spurious propellant. At the limit of credible MPD operation, the specific impulse depends on propellant properties only, and varies from about 3000 sec for lighter propellants, to about 400 sec for heavier propellants. In the same range, the maximum credible MPD efficiency varies from about 30% to about 10%. However, the efficiency depends on other MPD conditions also.

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Detailed background and related work, regarding our experiments, is presented in Refs. 1–4. It has been documented[1] that in our work the thrust is given by: $T = bJ^2$, where $b = 10^{-7}[(\frac{1}{2}) + \ln(r_A/r_C)]$, in MKS units, is the familiar coefficient of the MPD geometry, in terms of r_A and r_C, (anode and cathode radii). Also, in Refs. 1 and 4, we document how given flow rates are metered and supplied to the MPD thruster, during the quasi-steady operation. Representative examples of MPD current and voltage pulses are illustrated in Fig. 1. Each case is a dual beam shot of current (upper trace) and voltage (lower trace), with a common time origin and a sweep rate of 0.5 msec/cm. In each case, MPD breakdown takes place at about $t = 2$ msec and the current and voltage pulses follow. The two straight traces, before MPD breakdown, correspond to the zero current signal and to the voltage, V_0, at which the capacitor bank has been charged. All cases refer to an argon flow rate of 5.6 g/sec and all current deflections are at 6.5 ka/cm. MPD voltage deflections are at 50 v/cm in cases A, B, and C, and at 100 v/cm in cases D and E. With such information, obtained over the aforementioned ranges of experimental conditions, we have been able to evaluate the thruster performance. As mentioned, we have found that $(J^2/\dot{m})$ has a critical value, beyond which the thruster operation becomes increasingly erratic and decreasingly credible.

Two rather conspicuous and sharp signs of criticality are the onset of noisy and unstable operation as well as a sharp increase of the MPD impedance. Both these effects are clearly illustrated in the examples of Fig. 1, when $(J^2/\dot{m})$ exceeds about 45 (ka)^2/g-sec^{-1}. These demarcation points as well as the onset of thruster erosion, (with the inevitable introduction of spurious propellant), have been used for the experimental identification of the critical values: $(J^2/\dot{m})_c$, which are reported in Tables 1 and 2.

An inspection of these data shows that they depend on propellant type and on MPD geometry. In fact, the aforementioned critical values are in fair agreement with the analytical representation: $(J^2/\dot{m})_c = [(2eN_0)^{1/2}/b] \cdot (V_i/M)^{1/2}$ where V_i and M are the ionization potential of molecular weight of the propellant, N_0 is the number of particles per mole and e is the electron charge.

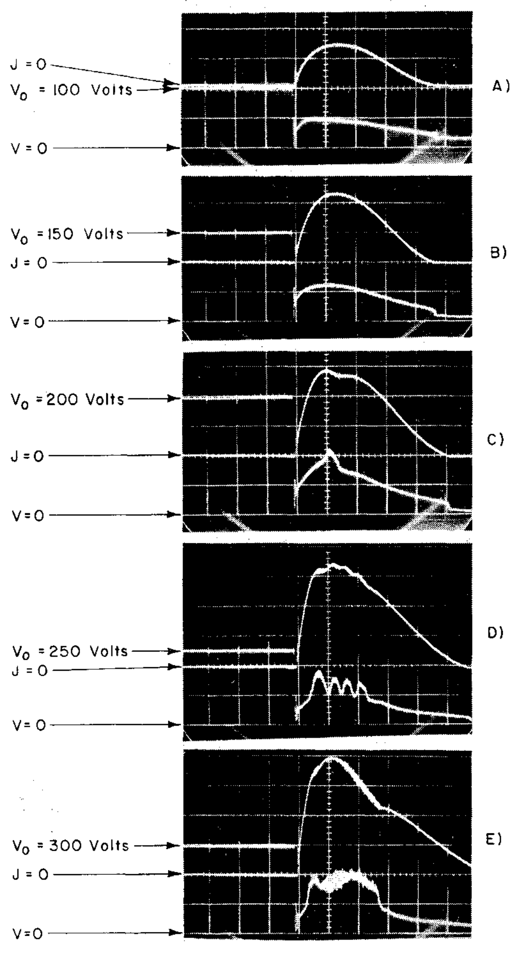

Fig. 1 Five separate cases illustrating data of current and voltage pulses of the MPD, (3-in. anode, $\frac{3}{4}$ in. cathode).

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Table 1 MPD performance at critical conditions for seven different geometries and for four different flow rates of argon propellant

Entry No.	$\dot{m}$ g-sec^{-1}	$2r_A$, in.	$2r_C$, in.	$(J^2/\dot{m})_c$, (ka)^2/g-sec^{-1}	$(JV)_c$, kw	Z_c, mohm	$(I_{sp})_c$, sec	e_c, %
1	1.1	2	$\frac{1}{2}$	45	420	8.5	860	10
2		2	$\frac{3}{4}$	58	440	6.9	880	10
3		2	$\frac{5}{4}$	91	540	5.4	910	8
4		3	$\frac{3}{4}$	45	300	6.1	900	15
5		4	$\frac{1}{2}$	33	460	12.7	900	10
6		4	$\frac{3}{4}$	35	450	11.7	800	8
7		4	$\frac{5}{4}$	45	390	7.9	760	8
8	2.2	2	$\frac{1}{2}$	45	630	6.4	870	13
9		2	$\frac{3}{4}$	55	730	6.0	850	11
10		2	$\frac{5}{4}$	90	940	4.7	910	10
11		3	$\frac{3}{4}$	45	540	5.5	920	17
12		4	$\frac{1}{2}$	29	580	9.1	800	12
13		4	$\frac{3}{4}$	37	630	7.7	840	12
14		4	$\frac{5}{4}$	45	750	7.5	780	9
15	5.6	2	$\frac{1}{2}$	46	1100	4.3	900	21
16		2	$\frac{3}{4}$	58	1200	3.7	900	19
17		2	$\frac{5}{4}$	95	1700	3.2	950	15
18		3	$\frac{3}{4}$	46	1200	4.7	900	19
19		4	$\frac{1}{2}$	27	1100	7.3	700	12
20		4	$\frac{3}{4}$	36	1500	7.4	800	12
21		4	$\frac{5}{4}$	40	860	3.8	700	16
22	12.0	2	$\frac{1}{2}$	44	2000	3.8	860	22
23		2	$\frac{3}{3}$	56	1900	2.8	850	23
24		2	$\frac{5}{4}$	96	3200	2.7	980	18
25		3	$\frac{3}{4}$	44	1500	2.8	880	28
26		4	$\frac{1}{2}$	21	1700	6.7	600	13
27		4	$\frac{3}{4}$	33	3000	7.5	750	11
28		4	$\frac{5}{4}$	40	2000	4.2	680	14

The remaining columns in Tables 1 and 2 summarize the important quantities: MPD input power, impedance, specific impulse, and thrust efficiency, all determined at the corresponding critical values of $(J^2/\dot{m})$. According to aforementioned analytical expressions, the critical specific impulse is expected to be independent of the MPD geometry and to depend on the propellant only, (mainly as $M^{-1/2}$). These situations are observed, indeed, in the experimental data of Tables 1 and 2.

Finally, regarding the thrust efficiency at the critical point, we have found that the experimental data are fairly well represented by the relation: $e_c = (b/2)(I_{sp})_c/Z_c$. This relation may be derived

Table 2 MPD performance at critical conditions for five different propellants and at several flow rates. The MPD thruster geometry is fixed at 3 in. anode, $\frac{3}{4}$ in. cathode

Entry No.	Propellant	$\dot{m}$, g-sec^{-1}	$(J^2/\dot{m})_c$, (ka)^2/g-sec^{-1}	$(JV)_c$, kw	Z_c, mohm	$(I_{sp})_c$, sec	e_c, %
1	Helium	0.7	150	1100	10.5	2900	27
2		1.5	127	2200	11.5	2500	21
3		4.1	140	5600	9.8	2700	27
4	Neon	1.6	63	830	8.2	1200	14
5		4.0	64	1600	6.3	1200	18
6		8.5	68	3400	5.9	1300	21
7	Argon	1.1	45	300	6.1	900	15
8		2.2	45	540	5.5	920	17
9		5.6	46	1200	4.7	900	19
10		12.0	44	1500	2.8	880	28
11	Krypton	3.3	30	540	5.5	600	11
12		8.6	30	1000	3.9	590	15
13		18.0	32	1800	3.1	620	19
14	Xenon	4.1	24	460	4.7	490	11
15		10.4	25	980	3.8	490	13
16		22.3	24	1900	3.6	470	13

by simple algebraic manipulations of aforementioned expressions and is very informative in the following sense: the choice of (r_A/r_C) fixes b; moreover, the choice of the propellant fixes $(I_{sp})_c$. All other MPD conditions may be chosen so that Z_c is minimized. This then should optimize the thrust efficiency.

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