Pressure and Current Effects on the Thermal Efficiency of an MPD Arc Used as a Plasma Source

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Theme

IN several types of laboratory experiments, such as magnetoplasmadynamic power generation, gas dynamic lasers, and basic gaseous plasma studies, a reliable and efficient continuous source of plasma is useful. This paper describes one such source, the magnetoplasmadynamic (MPD) arc operated without an applied magnetic field and presents data on its thermal efficiency, principal heat loss, and arc voltage over a range of argon mass flow rates not previously reported and at several arc currents. A comparison between this data and an existing empirical theory is also made with good agreement.

The MPD arc has been studied extensively for possible use as a spacecraft thruster. For this application the arc is operated at low propellant mass flow rates and low-pressure levels. As a plasma source, the MPD arc was found not to require an applied magnetic field; it was also found that the arc can be operated reliably at argon flow rates between 0.08 and 44 g/sec, arc chamber pressures between 26 and 950 torr, and d.c. currents between 200 and 2000 amp. Within these limits the arc produces a steady stream of argon plasma at a thermal efficiency as high as 90%, and with an enthalpy between 4×10^5 and 4×10^7 joule/kg. Except for the lower current limit (200 amp), these limits on the operating parameters were dictated by the available equipment and, as far as is known, do not represent limits on the MPD arc itself. At currents below 200 amp the arc head was not reliable.

Contents

A schematic drawing of the MPD arc head, as used in this study, is shown in Fig. 1. The arc head is axisymmetric with a central 2% thoriated tungsten cathode and a concentric water-cooled copper anode and face plate. The face plate was not electrically insulated from the anode. The anode and cathode were electrically insulated from each other by a 1.43-cm-long boron nitride insulator ring. The gas was injected into the arc chamber through an annulus at the base of the cathode and flowed out between the electrodes.

The arc head was operated inside a vacuum tank and the ambient pressure varied linearly with mass flow rate from approximately 0.1 to approximately 10 torr at the maximum flow rate. Standard calorimetry techniques were used to measure, separately, the heat transfer to the cathode base plate, anode, and face plate. In addition, measurements of argon mass flow rate, arc chamber, and vacuum tank pressure, arc current and voltage were made for each data point. The arc was started by simply switching the power supply to the electrodes. This power supply provides 320 v d.c. at zero current and this was sufficient to start the arc with an arc chamber pressure of 10 torr and a mass flow rate of 0.5 g/sec. Once the arc was struck, the current and mass flow rate could be changed throughout their respective ranges without extinguishing the arc.

The thermal efficiency η_{TH} computed from the measured total power consumption and the total power lost to the cooling water is shown in Fig. 2 as a function of the arc chamber pressure P_c, for a constant arc current I of 1000 amp. The chamber pressure was increased by increasing the argon mass flow rate $\dot{m}$ from 0.13 to 38 g/sec for this figure. The single most important result of this study is that at high $\dot{m}$, η_{TH} is very high, reaching 90% at 200 amp and 43 g/sec. At low P_c the sharp increase in η_{TH} with P_c can be traced to the effect that P_c has on the total heat loss to the electrodes, Q_T. This total heat loss is

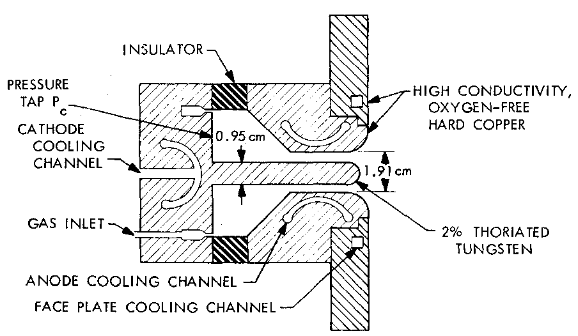

Fig. 1 Concentric electrode arc head schematic.

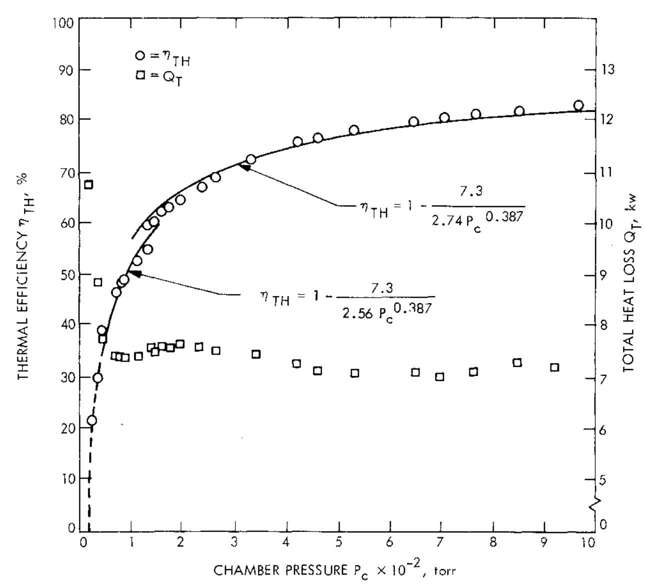

Fig. 2 Effect of pressure on thermal efficiency and total heat loss at 1000 amp.

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Index categories: Plasma Dynamics and MHD; Research Facilities and Instrumentation; Electric and Advanced Space Propulsion.

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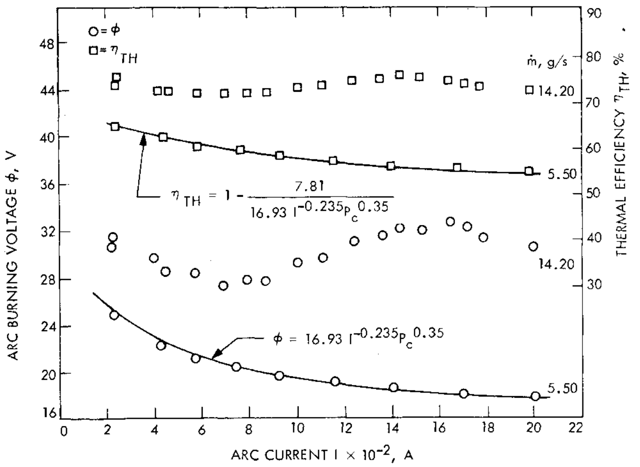

Fig. 3 Effect of argon mass flow rate and arc current on thermal efficiency and arc voltage.

also shown in Fig. 2 where it can be seen that below 70 torr Q_T is a strong function of P_c. It is believed that this sharp decrease of Q_T with increasing P_c at low pressure is caused by a decreasing anode sheath potential drop with increasing P_c. This drop was also seen as a slightly decreasing arc voltage ϕ as P_c was increased up to 70 torr. Above 70 torr Q_T is almost independent of P_c, as shown in Fig. 2, but ϕ increased with $P_c^{0.387}$ causing a further rise in η_{TH}. The sudden increase in η_{TH} at 138 torr was caused by a similar increase in ϕ of approximately 1 v. This is usually referred to as a mode change and probably represents a change in the arc positive column since the jump did not effect Q_T.

Also shown in Fig. 2 is the following empirical expression for η_{TH} developed from the results of Refs. 1 and 2

$$\eta_{TH} = [1 - \phi_A/[C_0 I^m] P_c^{\,n}] \quad (1)$$

where ϕ_A represents the power loss to the anode per ampere of arc current and $C_0 I^m P_c^{\,n}$ is an expression for ϕ. The proportionality constant C_0, the exponents m and n, and ϕ_A are determined experimentally. Basing η_{TH} on losses at the anode only is a simplification that is justified by the finding that approximately 95% of Q_T was anode heat loss. Note that for the curves in Fig. 2, ϕ_A is taken as constant and ϕ as an increasing function of P_c for the entire pressure range. This is not correct for pressures below 70 torr, for this case, since it was found that ϕ_A decreased and ϕ was approximately constant at 14 v as P_c was increased up to 70 torr. The fact that the curve fits the data below 70 torr is the result of compensating errors. A more accurate theory would have to take into account the effect of pressure on the anode sheath drop at low pressures.

Constant I, variable $\dot{m}$, experiments like that shown in Fig. 2 were also made at 200, 400, and 1600 amp with similar results. In addition, ten runs were made by holding $\dot{m}$ constant at values between 0.49 and 44.15 g/sec and varying the arc current between approximately 200 and 2000 amp. Two of the arc characteristics obtained in this way are shown in Fig. 3. For $\dot{m}$ up to 5.50 g/sec, P_c up to approximately 200 torr, we obtained negative characteristics which are normal for free-burning arcs. However, as is seen in Fig. 3, at higher mass flow rates the voltage characteristics oscillate with current. These oscillations could be the result of energy loss by radiation from the arc at higher pressures. Also shown in Fig. 3 is the η_{TH} corresponding to the two characteristics. The similarity in shape between the η_{TH} and ϕ curves in Fig. 3 result from the fact that ϕ_A is independent of I.

Table 1 Summary of results

I, amp	$\dot{m}$, g/sec	ϕ_A, v	C or C_0	m	n	P_{cr}, torr
200	variable	7.0	8.94	...	0.247	26
400	variable	7.9	4.52	...	0.313	50
1000	variable	7.3	2.74	...	0.387	70
1000	variable	7.5	3.07	...	0.392	80
1600	variable	7.4	1.16	...	0.519	130
variable	0.49	8.26	19.54	−0.248	...	...
variable	2.00	7.78	17.41	−0.221	...	...
variable	4.00	7.52	17.10	−0.253	...	...
variable	5.50	7.81	16.93	−0.218	...	...
variable	7.10	7.64	...	...	...	...
variable	10.65	7.41	...	...	...	...
variable	14.20	7.58	...	...	...	...
variable	23.43	7.38	...	...	...	...
variable	32.00	7.43	...	...	...	...
variable	44.15	7.40	...	...	...	...

The results of the constant current and constant mass flow experiments are summarized in Table 1 in terms of ϕ_A, C_0 or $C \equiv C_0 I^m$, m and n. In addition, the pressure at which Q_T drops to its first minimum, 70 torr in Fig. 2, are listed as P_{cr} for the constant current experiments. In all cases ϕ_A was found to be independent of I and only moderately dependent on P_c for $P_c > P_{cr}$. C_0 and m could only be determined for the four low $\dot{m}$ characteristics since for $\dot{m}$ above 5.50 g/sec we did not get simple negative characteristics. The values of n in Table 1 compare well with a value of 0.368 computed from the results of Ref. 1. In addition, by cross plotting the ten characteristics, 12 more values of n were determined at currents between 200 and 2000 amp. It was found that n was 0.374 ± 0.015 for I between 500 and 1600 amp and dropped smoothly to 0.270 at 200 amp and to 0.300 at 2000 amp.

References

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