initial droplet radius, f is fraction of droplet evaporated, w^* is initial ratio of liquid mass flow to gas mass flow, and F_e is the efficiency factor for capture of electrons by water droplet. For the typical streamtube shown in Fig. 1 water was injected from the side of the vehicle and entered the streamtube at a distance s_1/d_N from the shock with d_N = 30.48 cm.

Comparison between these "air + water" curves shows that a large portion of the reduction in N_e, a factor of 10 to 20, is not due to the recombination at the surface of the droplets. Instead, it is due to removal of the condition of local ionic equilibrium which existed before water injection. This is seen in Fig. 2, which shows a decrease in N and O atom concentrations, γ, due to the gas reactions resulting from H_2O dissociation. The rapid removal of the N atom concentration results in a shift away from local equilibrium for the reaction, $NO^+ + e^- \rightleftharpoons N + O$, thus allowing gas phase recombination of $NO^+ + e^-$ to a "self-limiting" level which is based on the local flow velocity and the weakly temperature dependent recombination rate constant.[2] Cooling could not be a factor in shifting from the local equilibrium level to the "self-limiting" level since the temperature of the water + air mixture was actually slightly higher than the temperature of the air without water addition. Calculations of the dilution effect were made and found to be of secondary importance for the amount of water used.

The method presented here for electron density reduction would not be expected to work for blunt-nosed vehicles traveling at velocities much lower than 20,000 fps or much higher than 30,000 fps.

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Anode Current and Heat Flux Distribution in an MPD Engine

K. T. Shih*
Convair Division of General Dynamics, San Diego, Calif.

Introduction

EXPERIMENTAL results of an anode heat-transfer study of an MPD arc have been previously reported by the author, using a solid anode for the measurement of the total quantities,[1] and a longitudinally segmented anode for the local measurements.[2] Also, a simple anode heat-transfer model was established by which the anode heat flux, Q, may be expressed by

$$Q = I(5kT_e/2e + U_a + \phi) + Q_{cr} \tag{1}$$

where I is the arc current, k is the Boltzmann constant, e is the electron charge, T_e is the electron temperature outside the anode fall, U_a is the anode fall, ϕ is the work function of the anode material, and Q_{cr} is the anode heat flux due to convection and radiation. Based on this anode heat-transfer model, it was found that the major part of the anode heat flux is carried by the electron current.

Received October 13, 1969. The author gratefully acknowledges stimulating discussions with A. V. Larson and the skillful laboratory work of O. J. Neller. A part of this work was presented as Paper 69-244 at the AIAA 7th Electric Propulsion Conference, Williamsburg, Va., March 3–5, 1969.

* Senior Research Engineer, Sensor Technology. Member AIAA.

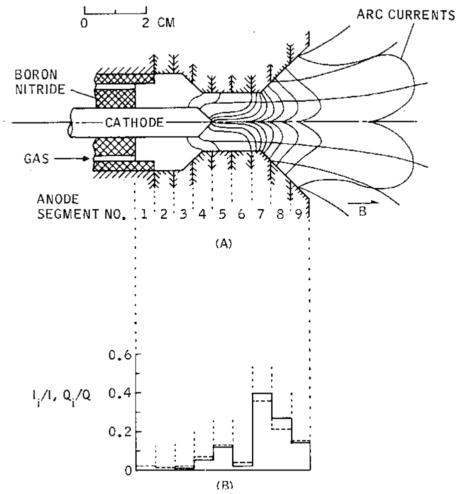

Fig. 1 A: Schematic of MPD arc engine with segmented anode. B: Typical anode current (solid lines) and heat flux (broken lines) distributions, Argon, $\dot{m}$ = 26.5 mg/sec, I = 300 amp, B = 1.6 kgauss, where $I = \Sigma I_i$, $Q = \Sigma Q_i$.

Current distributions have been obtained in the exhaust of an MPD arc by using Hall-effect sensors[3,4] and various search coils.[5] Except for the result of Cann,[3] it was found that only 15% or less of the arc current flows downstream of the anode nozzle. Hence, it is likely that most of the energy and momentum transfer in the arc occurs upstream in the anode nozzle. Due to the experimental difficulty, no current distribution data within the anode nozzle has been measured. In this work, an axially segmented anode is used to measure the axial anode current and heat flux distributions. These distributions provide information about where the important ionization, current, and heat effects take place, and the extent of the high current density zone. They also serve as an independent check of the anode heat-transfer model.

Experimental Apparatus

The engine assembly is shown schematically in Fig. 1a; the anode configuration consists of nine segments cut perpendicularly to the electrode center line. Each segment is isolated both electrically and thermally from the neighboring segments. All segments are water-cooled and connected to a common base ring through individual shunts. The segmented heat fluxes are measured by calorimetric methods, and the segmental currents are obtained by the voltage drop across the shunts. Experiments are conducted in a vacuum tank with a background pressure of less than one micron. Reference 6 presents a detailed description of the test facility.

Experimental Results

Anode current and heat flux distributions have been obtained for the MPD engine in argon by using a segmented anode over a current range from 100 to 500 amp; at mass flow rates from 10 to 40 mg/sec and applied magnetic field strength (measured at the cathode tip) from 0.3 to 3 kgauss. This range of parameters covers both spoke and no-spoke mode.[6,8]

Figure 1b shows typical distribution curves of anode current and heat flux. In this figure, the solid and broken lines represent the current and heat flux distribution, respectively. Generally speaking, the anode current attachment is quite diffuse; it is certainly less constrictive than that predicted by Refs. 5 and 7. The distribution assumes a maximum of about 45 to 50% of the total current to one segment at the

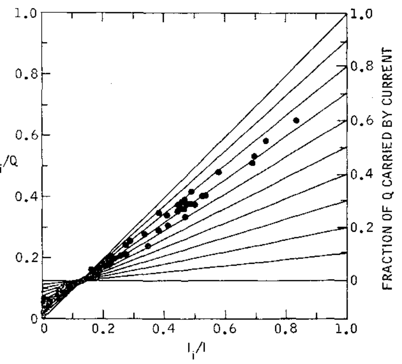

Fig. 2 Segmental anode heat flux vs current.

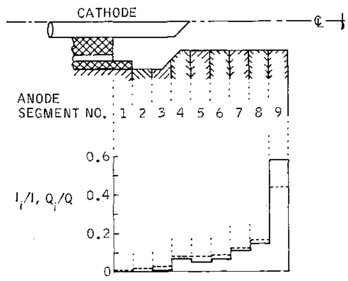

Fig. 3 Typical anode current (solid lines) and heat flux (broken lines) distributions of a cylindrical anode. Argon, = 25 mg/sec, I = 300 amp, B = 3 kgauss.

downstream end of the anode throat. A peculiar second hump inside the throat is also observed. The second hump is generally small and is considered to be of secondary importance. The distribution has been studied as a function of arc current, magnetic field strength, mass flow rate, and cathode position. For the three major downstream segments, the distribution is rather insensitive to the total arc current or applied magnetic field. However, increasing the mass flow rate or moving the cathode downstream pushes the current downstream. The current distribution on the upstream segments is strongly affected by most of the parameters.

Rogowski coils wrapped around the shunts connecting anode segments were used to detect the a.c. component of the segment currents. In addition, a sweeping Langmuir probe[8] was used to detect the spoke and no-spoke mode. When the engine is operated in a spoke mode, the segmental currents oscillate at the same frequency of the rotating spoke. The amplitude of the current oscillation in any segment is proportional to and of the order of 10% of the average current to the segment. For the steady-state measurements, no sudden changes on axial current and heat flux distribution can be found between the spoke and no-spoke modes.

With the knowledge of the anode current axial distribution, the arc current lines in the discharge are drawn schematically in Fig. 1a. These current lines have been slightly modified from those given in Ref. 5.

In Fig. 1b, the similarity between the current and heat flux distribution curves is particularly striking. These results can be interpreted with the anode heat transfer mode of Eq. (1), which shows that the heat flux to the anode is linearly related to the current. A collection of segmental anode heat-transfer data that covers a range of parameters is summarized in Fig. 2, in which the lines of the fraction of anode heat flux carried by current are constructed by using Eq. (1). Within the data scattering, it can be seen that the measured points follow a straight line as described by the model, and that about 70 ± 15% of the anode heat flux is carried by the arc current. Further, the values of $(5kT_e/2e + U_a + \phi)$ and Q_{cr} may be estimated from the slope and the intersection of the straight line. For the parametric ranges covered in this study, the value of $(5kT_e/2e + U_a + \phi)$ is between 10.6 and 15.2 v, and Q_{cr}/I between 3.3 and 6.2 v. These values are in good agreement with the results of the experiments with the longitudinally segmented anode,[2] which was operated in much higher background pressure. It may be concluded that background pressure has negligible effect on the anode heat-transfer data.

In this experiment, for the parameter range covered (limited by the existing equipment), no definite parametric trends are observed. The detectable level is determined by the data scatter. Over all, 60% of the input power goes into the anode; thus, the thermal efficiency is less than 40%.

Interesting observations are obtained when some segments are disconnected electrically, so that the anode current attachment is forced to a certain position. Normally, when all segments are electrically connected, the current distribution shows a maximum at the downstream end of the anode throat, as previously described. In this experiment, either the upstream anode segments are disconnected so that the anode attachment is pushed downstream or vice versa. In both cases, the arc voltage shows a drastic increase, especially when the attachment is pushed in the downstream direction. The total anode heat flux also shows a substantial increase. However, the anode heat-transfer model still holds and there is no improvement in the thermal efficiency. Actually, the efficiency decreases when the anode attachment is pushed upstream. When the arc attachment is forced out of its normal position, the arc voltage increase is consistent with the Steenbeck's minimum principle,[9] which requires that the arc current take a path of smallest voltage drop. The increase of the anode heat flux may be caused by a greater anode fall, which is suggested by an increase of approximately 10 v in $(5kT_e/2e + U_a + \phi)$.

A segmented cylindrical anode without a divergent nozzle is also used to study the effect of anode geometry. Figure 3 shows typical distribution curves of anode current and heat flux of such an anode configuration. Note that the maximum current density moves farther downstream toward the anode muzzle, as does the heat flux density—but there is no apparent change on thermal efficiency.

Some experiments have been also performed using ammonia as the working fluid. The arc voltage for the ammonia arc (60–90 v) is found to be much higher than the argon arc (26–32 v). However, the results of anode current and heat flux distribution are similar to those obtained from the experiments in argon atmosphere.

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