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EXPERIMENTAL HEAT TRANSFER DISTRIBUTION IN AN ARC CONSTRICTOR OF VARIABLE CROSS-SECTIONAL AREA

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NOMENCLATURE

E, arc voltage measured with respect to the cathode;
h_m, plasma mixed-mean enthalpy;
I, arc current;
m, mass flow rate of plasma operating gas;
Nu, local Nusselt number,

$$\frac{2r\,q_w}{k_m(T_w - T_m)};$$

p, static pressure in the nozzle;
p_B, exhaust plenum pressure;
q_w, total wall heat flux;
r, duct radius;
T_m, equilibrium temperature corresponding to the mixed-mean enthalpy;
T_w, wall temperature.

INTRODUCTION

As a result of interest in the commercial and research applications of high-temperature plasma, considerable work has been done to determine the thermal and electrical characteristics of arc-generated plasmas. To date, however, studies have focused almost exclusively on the properties of subsonic, constant-diameter, tube-arc plasmas, and little has been done to determine the properties of supersonic arc plasmas confined in variable area ducts.

The objective of this communication is to summarize the key results of a recent study [1] to determine the influence of variable areas, operating pressure, supersonic flow, and compression shock fronts on the total wall heat flux from confined arc plasmas.

APPARATUS

The arc constrictor geometries used for this study are shown in Fig. 1. Both nozzle arrangements are formed by stacking together copper segments of $\frac{1}{4}$-in. width, which are individually water-cooled and thermally and electrically isolated from each other. A total of 10 and 14 such segments are used to form the arc heating regions of nozzles A and B, respectively. From an energy balance performed on the cooling water to each segment and from measurement of the voltage and pressure at each segment, the axial distribution of q_w, E, p, h_m, and T_m are determined. Distributions have been obtained for an Ar gas at operating arc currents of 50, 80, 100 A and for gas flow rates in the range from 0·02 to 0·09 lb_m/min. For each test run, the pressure upstream of the cathode is maintained close to one atmosphere and flow conditions in the nozzle are varied through adjustment of the back pressure, p_B, in the exhaust plenum assembly. All supporting equipment and diagnostic procedures are described by Link [1] and Lukens [2].

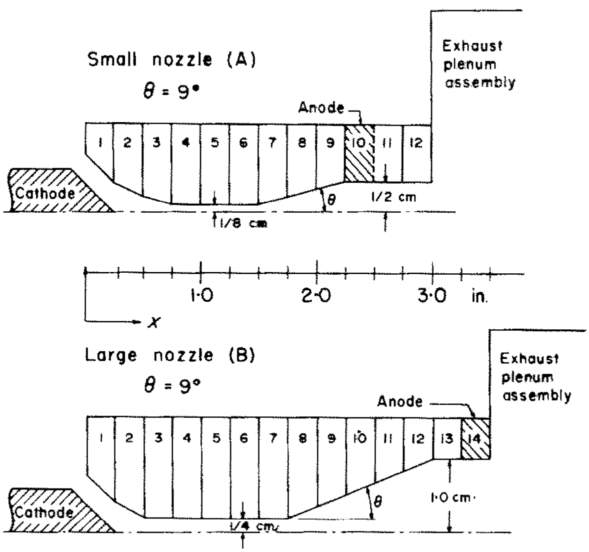

FIG. 1. Nozzle configurations of this study.

RESULTS

Results, which are typical of the axial heat flux distribution obtained for all test runs, are shown in Fig. 2 for nozzle A and selected operating conditions. For each distribution, the flow is entirely subsonic. The total wall heat flux increases in the converging section, reaches a peak at the throat, decreases in the diverging region, and rises to a secondary peak at the anode. The form of the distribution upstream of the anode is similar to distributions typically observed for the nozzle flow of high temperature unionized gases [3]. However, the shape of the heat flux distributions cannot be explained entirely as an area effect, since plots of the corresponding wall heat transfer rate (Btu/min) exhibit the same trend. Nor may the distribution be explained by suggesting that heating at the throat is in part due to the transfer of current from the arc to this surface. Considerable care is taken to insure electrical isolation between adjoining segments, and the anode remains the only current-carrying surface. A plausible explanation of the observed behavior is that in the converging section, as the wall moves towards the center line, the arc is developing radially outward. Hence, the separation between the wall and the periphery of the hot plasma core diminishes with increasing distance from the cathode, and the wall heat transfer increases accordingly. However, in the diverging region, it is suggested that the wall recedes from the center line at a faster rate than the outward radial development of the arc. Hence, a layer of relatively cool gas is maintained between the wall and the hot core of the arc. The thickness of this layer increases from its value at the throat to a maximum value at some point in the diverging region and then decreases to near zero at the anode, where the arc attaches to the wall. Accordingly, in the diverging region of the nozzle, the convection heat tranfer (the contribution of radiation is small for the current range of interest) should decrease, reach a minimum at the point for which the cool layer thickness is a maximum, and increase in the vicinity of the anode. A phenomenon which may also influence the heat flux distribution in the diverging section is that of flow separation from the duct wall at the throat exit. The occurrence of separation, with subsequent reattachment in the vicinity of the anode, would be consistent with the observed distribution.

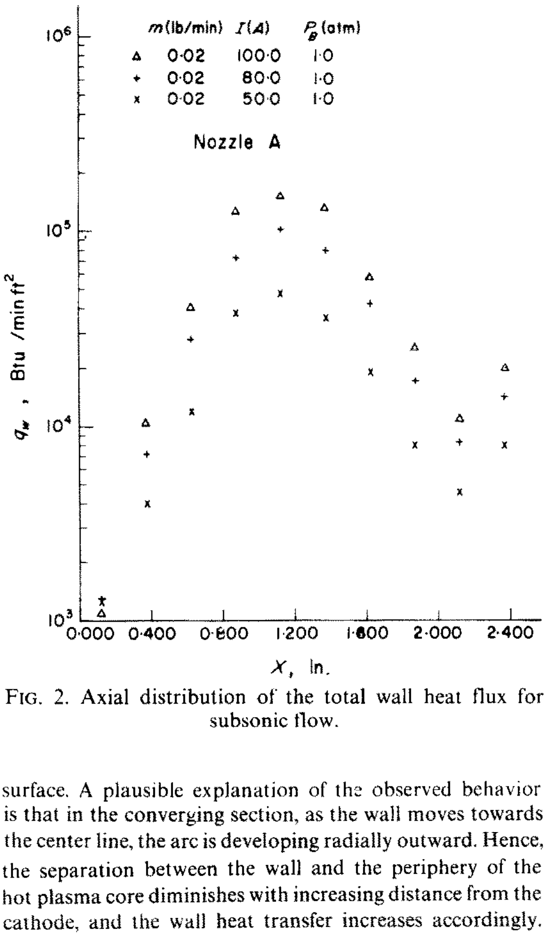

FIG. 2. Axial distribution of the total wall heat flux for subsonic flow.

In connection with Fig. 2, it is significant to note the almost order-of-magnitude difference between the heat flux at the throat and that at the anode. For constant diameter tube devices, it is well known that the most severely heated component of an arc constrictor is the anode; this is clearly not the case for the variable area constrictors of this study (little difference was observed between the results obtained for nozzles A and B). In addition, the magnitude of the heat flux, although strongly dependent upon current (Fig. 2), was observed to depend only weakly, and in no consistent way, on flow rate.

The influence of variable area on the axial distribution of p, E, h_m and T_m was also determined, and the results are reported by Link [1]. Although not exhibiting the pronounced area dependency which characterizes the wall heat flux, the axial distributions of these variables still differ from the distributions observed for constant diameter arcs [2]. Also, from the measured distributions, it was possible to compute the axial distribution of the Nusselt number, and typical results are shown in Fig. 3 for nozzle B. The distributions are similar in form to those obtained for q_w. The peak value for Nu occurs in the throat and is typically of the order of 10^3; the minimum value occurs in the diverging section and is of the order of 10.

The influence of supersonic flow on the wall heat flux is typified by the results of Fig. 4. The operating pressures for the two runs are identical (~ 1 atm) up to the throat exit, however, beyond this point, the flow becomes supersonic for the vacuum condition, with the pressure dropping rapidly and assuming a value of 0·7 psia at the nozzle exit. The pressure measurements also indicate the occurrence of a compression front at the nozzle exit. Although the heat flux distribution for the two runs is identical through the throat, there is a small, but clearly discernable, reduction in the wall heat flux for supersonic flow in the diverging region. This reduction is attributed primarily to the reduced thermal conductivity of the hot plasma core and secondarily to the reduced radiation (both of these effects result from a reduc-

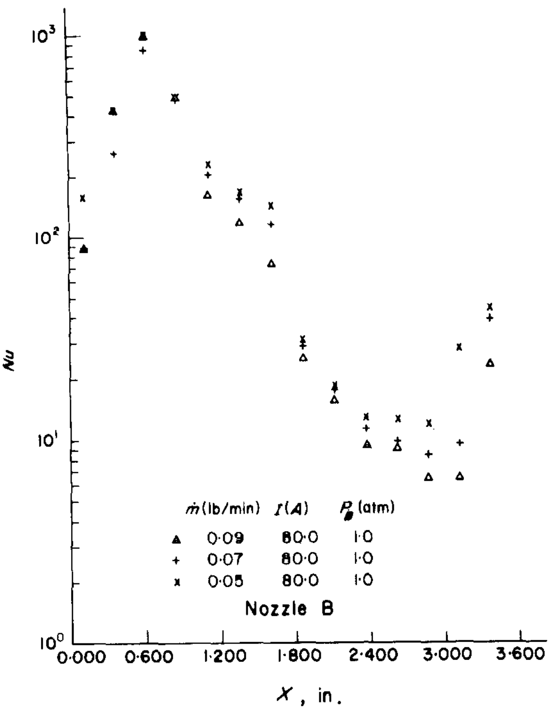

FIG. 3. Axial distribution of the Nusselt number for subsonic flow.

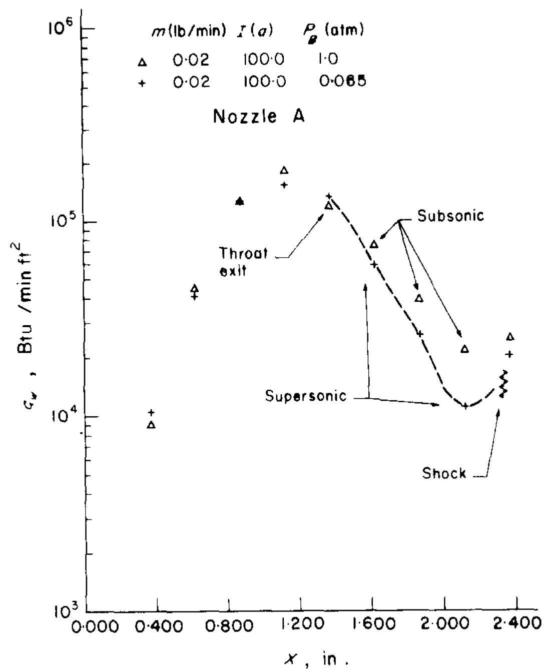

FIG. 4. Axial distribution of the total wall heat flux for subsonic and supersonic flows.

tion in the plasma pressure*). Also, as indicated in Fig. 4 and reinforced by other data [1], there was observed to be no dramatic change in the total wall heat flux due to the appearance of compression shocks.

SUMMARY

The essential results of this experimental study may be summarized as follows.

(1) The wall heat flux in a variable area arc discharge is significantly influenced by both the cross-sectional area and the arc current. The heat flux is found to be approximately proportional to I^2 and to $r^{-\frac{3}{2}}$. This functional dependence was obtained for both nozzles considered in this study. The heat flux is also found to be only weakly dependent on gas flow rate, operating pressure, supersonic flow, and the existence of compression shocks.

(2) The axial distributions of E and h_m are similar in form. For both nozzles, they increase with increasing current but are only weakly dependent on operating pressure, the existence of supersonic flow, and compression shocks. E is found to increase discernably with increasing $\dot{m}$, and h_m is found to decrease with increasing $\dot{m}$.

* For the plasma core temperatures of interest ($T \sim 20000°R$), thermal conductivity is known to decrease with decreasing pressure [4], in which case the diffusion of energy from the core to the outer gas layers will diminish.

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