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THEORY OF ARC CLOGGING IN NOZZLES

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Introduction: Previously a simple channel model has been used to successfully predict properties of low current arcs in forced flow in a nozzle [1]. The present paper extends this treatment to large currents when mass flow through the arc is an appreciable fraction of the cold gas flow surrounding the arc. It is necessary to solve the axial momentum and mass continuity equations to obtain the axial pressure and velocity distributions. At sufficiently large currents the arc diameter equals the nozzle diameter at some axial positions. Then ablation from the nozzle wall markedly increases the pressure within the nozzle.

Theory: It is assumed that the arc plasma can be represented as a function of axial position $z$ by area $A(z)$ and temperature $T(z)$, the arc being isothermal with radius. When the arc area attains the nozzle area it is assumed that all of the input electrical energy is absorbed at the nozzle wall either by thermal conduction or by the absorption of radiation. This energy then ablates wall material which is brought to the arc temperature and increases the plasma flow. This energy then ablates wall material which is brought to the arc temperature and increases the plasma flow. The basic conservation equations and Ohm's law define the quantities $E(z)$, $T(z)$, $V(z)$, $V_c(z)$, $P(z)$, $A(z)$ and $\dot{m}(z)$ where $E$ is the electric field, $V$ and $V_c$ the velocities of the plasma and cold gas respectively, $P$ is the pressure and $\dot{m}$ is the rate of mass entry into the arc in gm s$^{-1}$. Ohm's Law defines the electric field for any input current $I$ where $\sigma(T)$ is the electrical conductivity,

$$I = \sigma EA$$

(1)

The energy balance equation at the arc centre is

$$\rho \frac{\partial V}{\partial t} = -\frac{\partial P}{\partial z} - \rho \frac{\partial V}{\partial z}$$

(3)

$$\frac{\partial (\rho A)}{\partial t} + \frac{\partial (\rho V A)}{\partial z} = \frac{\partial (\rho c V (Q-A))}{\partial z} - \dot{m}$$

(4)

$$\frac{\partial (\rho_c (Q-A))}{\partial t} = -\frac{\partial (\rho c V (Q-A))}{\partial z} - \dot{m}$$

(5)

Equations (4) and (5) express mass continuity for the plasma and cold gas regions respectively; the subscript $c$ refers to the cold gas surrounding the arc and $Q$ is the nozzle area. Rather than solve an additional equation for axial momentum for the cold gas we assume that the Mach number of the plasma equals the Mach number of the cold gas.

Thus $V_c/A_c = V/A_c$

(6)

where "a" is the sonic velocity.

The energy balance equation integrated over a cross section of the arc column is

$$\frac{\partial (\rho h A)}{\partial t} = \rho E^2 - \frac{\partial (\rho h A)}{\partial z} + \dot{m} \ h_c$$

(7)

where $h$ is the enthalpy of the plasma. Because $h_c \ll h$ the term $\dot{m} \ h_c$ can be omitted. Equation (7) principally defines arc area when $A < Q$. However when the nozzle is clogged, i.e., when $A > Q$, this equation primarily determines the pressure in that for the steady state, $P$ increases until $\rho h V Q$ at the exit equals the input electrical power. It is assumed no ablation occurs before the arc core diameter attains the nozzle diameter.

Manipulating equations (2), (4) and (7) together with the identity $\dot{m} \ h_c = \rho c V (Q-A)$ it is possible to derive

$$\dot{m} = UA/(h+c) - UA/h$$

(8)

Thus we can eliminate $\dot{m}$ from the equations and avoid using equation (7).

Equations (3-5) and (7) are expressed in the time
dependent form both to enable time dependent calculations to be made and also to provide a means of iteration on arbitrary initial values of $T(z)$, $A(z)$ and $V(z)$ to obtain steady state solutions.

In the numerical results that follow, we have assumed that $\sigma$, $C_p$, $h$, $a$ are independent of pressure and taken values for air at 1 atmosphere. The values of $U$ and $\rho$ are assumed to be proportional to pressure. For cases where ablation is significant the material functions should be those of the ablated nozzle material but we have found that they differ only slightly at high temperatures from our calculations of material functions of teflon, PVC and perspex.

Results: In Fig. 1 are shown calculated arc radii as a function of axial position for various d.c. currents. In Fig. 2 the calculated pressure distributions are shown as a function of axial position. Above 2 kA, the arc restricts flow in the nozzle and the local pressure increases. In Fig. 3 the calculated axial Mach number distributions are shown for various currents. At 30 kA there is a stagnation point within the nozzle and a flow of plasma back into the high pressure tank.

The calculated volt-ampere characteristics are shown in Fig. 4, together with the temperature at the nozzle throat. Also shown is a curve calculated with the nozzle reversed, the throat then being near the exit.

Reference: