MECHANISMS FOR TEMPERATURE DECAY IN THE CONVECTION STABILIZED ARC

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ABSTRACT

The energy loss mechanisms - radial and axial convection, radial conduction and axial expansion - cooling the extinguished convection stabilized arc in nitrogen are assessed from a model based on the conservation equations for mass, momentum and energy. It is found that while radial convection is the dominant cooling mechanism, the contributions of the other mechanisms can be critical at certain times during the cooling period.

1. INTRODUCTION

The conservation equations for mass, momentum and energy have been used to model the behavior of the extinguished convection stabilized arc in a laval nozzle[1]. Radial profiles of the arc temperature and velocity are assumed to have a double Gaussian shape, while the axial profiles are obtained from a solution of the conservation equations. The nature of the physical processes influencing the decay of the arc, however, are not explicitly explored in Reference 1.

In this work, we use the integral energy conservation equation to first define the energy loss mechanisms responsible for cooling the decaying arc, and then to assess their relative magnitudes both axially in space and in time.

2. ARC MODEL

The extinguished arc channel and the surrounding hot gas mantle are described by a two zone model[1], Fig. 1. Each zone is characterized by a Gaussian radial temperature profile, described by its peak temperature T_1 or T_2 and an effective width parameter δ_1 or δ_2, respectively. As the arc channel and mantle cool, both the peak temperature and the effective width of the two zones change.

Both the decay rate of T_1 and the physical mechanisms responsible for it are of importance. However, the energy conservation equation is not cast in a form that exposes the comparative contributions of the various energy loss mechanisms to temperature decay. To overcome this difficulty, we define for the arc channel a mass averaged enthalpy h_{av}

$$h_{av} \equiv \frac{\int_0^{\delta_1} \rho h \, 2\pi r dr}{\int_0^{\delta_1} \rho \, 2\pi r dr} \cong \frac{\int_{T_B}^{T_1} \frac{\rho h}{p} \frac{dT}{T}}{\int_{T_B}^{T_1} \frac{\rho}{p} \frac{dT}{T}} \qquad (1)$$

where ρ is the density, h is the enthalpy, p is the pressure, and $T_B = \frac{T_1 - T_2}{e} + T_2$ is the temperature at $r = \delta_1$. Expression (1) indicates that h_{av} is only a function of T_1 and T_2. The rate of change of h_{av} can be written as

$$\frac{\partial}{\partial t} h_{av} = \left(\frac{\partial}{\partial T_1} h_{av}\right) \frac{\partial}{\partial t} T_1, \qquad (2)$$

having neglected the contribution of $\frac{\partial}{\partial t} T_2$ owing to the slower rate of cooling of the hot gas mantle. Thus, a determination of the rate of change of h_{av} allows us to find the temperature decay rate of the arc channel.

The rate change of h_{av} can be obtained from equation (1) to be

$$\frac{\partial}{\partial t} h_{av} = \frac{1}{(\bar{\rho} A)_I} \left[\frac{\partial}{\partial t} (\overline{\rho h} A)_I - h_{av} \frac{\partial}{\partial t} (\bar{\rho} A)_I \right], \qquad (3)$$

where $A = \pi \delta_1^2$, a bar over a quantity is its average value over the range $0 \leq r \leq \delta_1$, and the "I" subscript refers to the arc channel.

The various quantities appearing in expression (3) can be determined from the integral conservation equations developed in Ref. 1, obtaining

$$\frac{\partial}{\partial t} h_{av} = \left\{ \left[\rho_B \, 2\pi\delta_1 \left(- \frac{\partial \delta_1}{\partial t} - V_B \frac{\partial \delta_1}{\partial z} + V_{r_B} \right) (h_{av} - h_B) \right] + \left[h_{av} \frac{\partial}{\partial z} (\overline{\rho V} A) - \frac{\partial}{\partial z} (\overline{\rho h V} A) \right] - \left[4\pi \kappa_B (T_B - T_2) \right] + \left[(\bar{V} A)_I \frac{dp}{dz} \right] \right\} \Big/ (\bar{\rho} A) \qquad (4)$$

where V is the axial velocity, V_r is the radial velocity, κ is the thermal conductivity, and the "B" subscript refers to values at $r = \delta_1$; the "I" subscript for the averaged value is implied.

Equation (4) clearly separates the contributions of the various physical mechanisms towards the decay of h_{av} and, therefore, of T_1. These processes are in order of their appearance on the right hand side of (4), radial flow, axial flow, radial conduction and axial expansion cooling.

3. RESULTS

Simulation of the decay of an extinguished nitrogen arc as stipulated in Ref. 1, is carried out and the energy loss mechanisms defined in (4) are examined. The laval nozzle in which the activity occurs exerts its influence by fixing the axial pressure gradient profile. For the simulation studied here, the upstream nitrogen pressure is 23 bar and the pressure gradient profile imposed by the nozzle is that shown in Fig. 2.

The axial profiles of the various loss mechanisms of (4) for several time lapses after extinction are displayed in Fig. 3. Axial flow is seen to transport heat from the upstream to the downstream region. Expansion cooling is a significant mechanism which is often ignored. Both energy loss mechanisms peak out in the nozzle throat region coinciding with the peak in the axial pressure gradient, and thus, indicating a strong dependence on the laval nozzle geometry. Radial convection strongly cools the channel during the first 20 μsec causing a dramatic drop in its temperature. Subsequently, it contributes a major share to cooling the channel along its length. Radial conduction is seen to be the least significant cooling mechanism, except in the upstream stagnation region.

The effect of changing the initial conditions on the cooling rate of the arc channel were investigated. It is found that an increase in the initial channel temperature leads to a corresponding increase in the cooling rate for the first 30 μs, related to the plasma transit time in the nozzle, followed by a second cooling rate insensitive to the initial temperature.

Increasing the ambient pressure imposed by the upstream plenum, while retaining the same pressure gradient profile shape, did not result in any significant change in the cooling rate of the arc channel, except in the upstream region where the pressure increase slightly slowed the cooling rate, owing to the contribution of radial conduction.

4. CONCLUSION

The mechanisms of radial conduction, axial and radial convection and axial expansion for cooling the channel of an extinguished convection stabilized arc in nitrogen are defined and their relative magnitudes in space and time are explored. Radial convection is found to be the dominant cooling mechanism. Axial convection and expansion are very strong functions of the axial pressure gradient imposed by the laval nozzle. Radial conduction plays a minor role. Two time constants for the channel cooling can be discerned: one pertaining to the plasma transit time in the nozzle, the other for later times. Initial conditions on the arc channel influence the cooling rate during the transit time period, but has no influence later. An increase in the overall nozzle pressure does not have or influence on the channel cooling rate.

5. ACKNOWLEDGEMENT

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6. REFERENCES

(1) E. Richley and D. T. Tuma, IEEE Trans. Plasma Science, PS-8, 405 (1980).

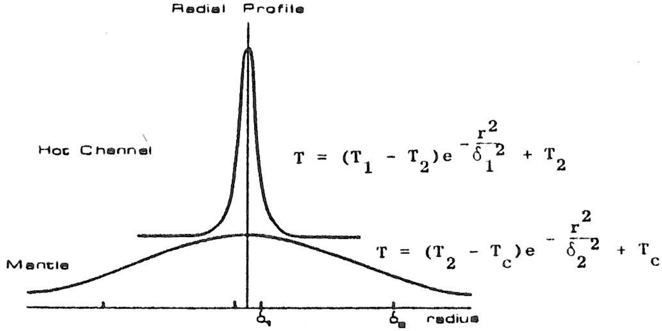

FIG. 1 Double Gaussian radial temperature profile of the arc channel and hot gas mantle.

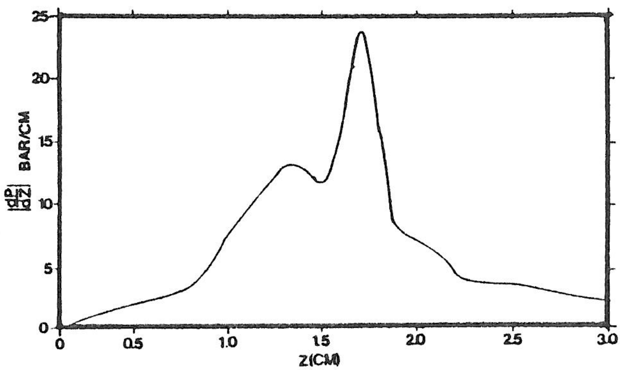

FIG. 2 Axial profile of the pressure gradient imposed by the laval nozzle.

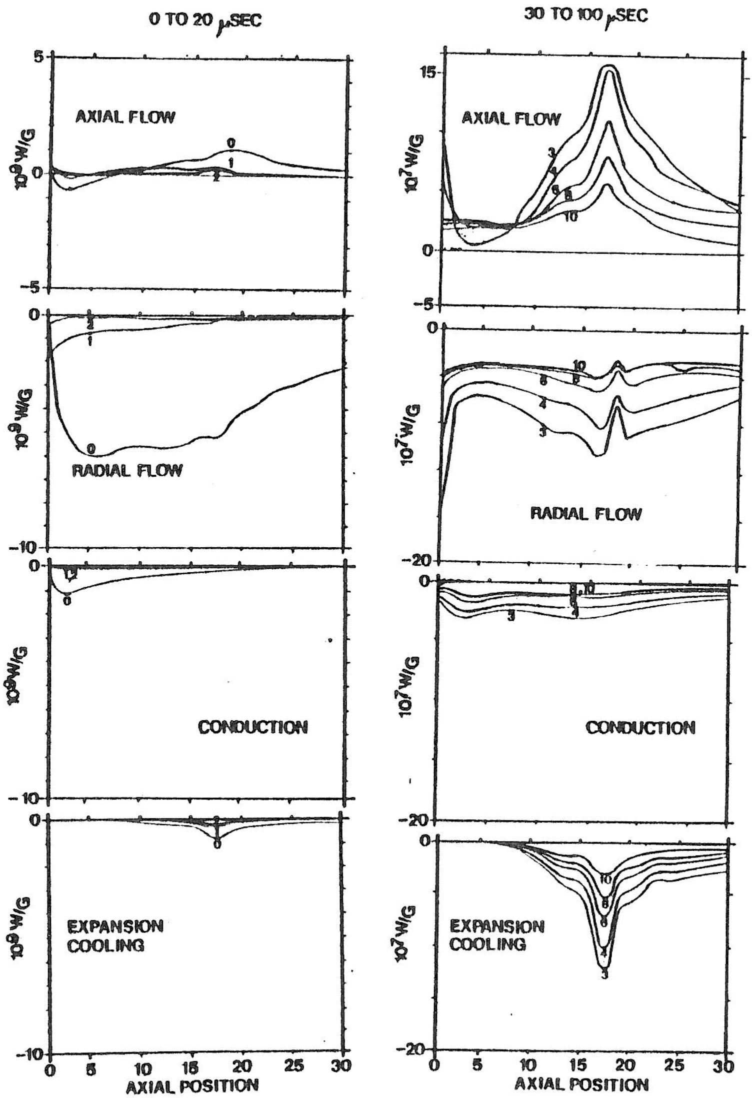

FIG. 3 Axial profiles of the energy loss mechanisms for temperature decay, as defined in equation (4). Labels refer to the time after extinction in units of 10 μsec.