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THEORETICAL MODEL OF CURRENT-ZERO BEHAVIOUR OF AXIALLY BLOWN ARC IN SF\textsubscript{6}

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Introduction

Much attention has been recently devoted to the study of current-zero behaviour of high pressure, a-c arc in supersonic nozzle flow /1-5/. Radial conduction enhanced by turbulence is the most effective energy transport mechanism within arc column in the current-zero region. In several papers /3-5/, transient behaviour of turbulence dominated arc with fixed radial temperature profile is theoretically studied, influence of electric circuit not being taken into account. We present the model of transient arc with time dependent radius \( r_c(t) \) and variable temperature profile. Interaction of arc with connected electric circuit is considered in model calculations. Both the arc-circuit interaction and the temperature-profile changes are supposed to have considerable effect on resulting dynamic arc behaviour.

Model Equations and Results of Calculation

Following assumptions are used to formulate model equations:

1. The only effective energy loss mechanism is radial heat conduction due to the turbulence. The turbulence originates in the shear flow associated with the existence of strong radial temperature gradient within the arc column.

2. Arc column has cylindrical symmetry.

3. Conductive arc core of radius \( r_c(t) \) is surrounded by the zone of intermediate temperature with fixed radius \( R \), for \( r=R \) the temperature reaches the temperature of cold gas. The same energy transport mechanism, as within the arc core, is effective in the intermediate zone.

The energy balance equation has then a form

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r k_t \frac{\partial T}{\partial r} \right) + \frac{\partial E^2}{\partial r} = C_p \frac{\partial T}{\partial t}
\]  

(1)

where effect of turbulence is described by turbulent thermal conductivity \( k_t \) /3-6/.

Conductivity \( k_t \) is given by /7/

\[
k_t = \frac{\varphi c_p \epsilon}{Pr_t}
\]

(2)

where \( \epsilon \) is turbulent kinematic viscosity and \( Pr_t \) is turbulent Prandtl number. To describe effect of turbulence on the arc, formulae for free turbulent shear flow were adapted /3-6/. \( \epsilon \) is considered to be proportional to the axial velocity \( c \) /6/, which is equal to the velocity of sound at given temperature. Prandtl number \( Pr_t \) is constant and approximately equal to 0.5 for free turbulent flow /7/. Then from (2) we obtain

\[
k_t = \lambda \frac{\varphi c_p c}{Pr_t}
\]

where \( \lambda \) is constant with the dimension of length. In Fig. 1 the temperature dependence of \( k_t/\lambda \) is given for SF\textsubscript{6} at 0.8 MPa, calculated from data in /3/.

For the solution of (1), it is convenient to introduce turbulent heat flux potential

\[
G = \int k_t/\lambda \, dt
\]

as variable instead of \( T \). Equation (1) acquires then form

\[
\frac{\partial^2 G}{\partial r^2} + \frac{1}{r} \frac{\partial G}{\partial r} + \frac{\partial E^2}{\partial r} = \frac{1}{\lambda c} \frac{\partial G}{\partial t}
\]

(3)

Arc current is given by Ohm's law

\[
i = 2\pi r e \int r \, \varphi \, dr
\]

(4)

Equations (3) and (4) with unknowns \( G(r,t), E(t) \) can be solved using data of transport properties of the gas \( \varphi(G), c(G) \) together with circuit equations. The material functions \( \varphi(G) \) and \( c(G) \), which determine the effect of gas properties on the arc behaviour, are given in Fig. 2 for SF\textsubscript{6} at \( p = 0.8 \) MPa.

Calculations were made for the circuit with serial inductance \( L \) and parallel capacity \( C_1 \) and resistive-capacity \( R C_2 \) branches. Equations (3), (4) together with circuit equations were normalized to reduce number of independent constants. Nondimensional energy equation and Ohm's law are given by

\[
G = \frac{\varphi c_p \epsilon}{Pr_t}
\]
\[
\frac{\partial^2 \hat{G}}{\partial x^2} + \frac{1}{x} \frac{\partial \hat{G}}{\partial x} + \frac{\partial \phi}{\partial x}^2 = \eta \frac{1}{\hat{C}} \frac{\partial \hat{G}}{\partial \tau} \tag{5}
\]

\[
\hat{\tau} = x \frac{\partial}{\partial x} \int x \phi \, dx \tag{6}
\]

where \( \hat{\delta}, \hat{\phi}, \hat{\gamma} \) are functions normalized to their axial value at \( t=0, \int \phi \, dx = \frac{E}{E_0}, \int \phi \, dx = \frac{x}{R} \) and \( \tau = t/\gamma \), where \( \gamma \) is characteristic time constant. The behaviour of arc in a given circuit is determined by two nondimensional parameters

\[
\int = \frac{R^2 \beta^2}{\lambda \gamma} \tag{7}
\]

\[
\gamma = \frac{R^2}{\lambda \gamma} \tag{8}
\]

further by the initial profile \( G(x,t=0) \) and initial axial value \( G_{ao} \), which define also the value of parameter \( X = \left( \int x \phi(x,t=0) \, dx \right)^{-1} \).

The Bessel profile of \( G \) within conductive core and logarithmic profile in intermediate region are supposed to occur at time \( t=0 \)

\[
\hat{\delta}(x, t=0) = \hat{\delta}_h + (1-\hat{\delta}_h)J_{\alpha/1}(x) \quad \text{for} \quad x > x_{co} \tag{9}
\]

\[
\hat{\delta}(x, t=0) = \alpha_2 \ln x \quad \text{for} \quad x_{co} < x \leq 1 \tag{10}
\]

where \( x_{co} \) is a normalized radius of conductive core at \( t=0, \hat{\delta}_h = \gamma H/G_{ao} \), where \( \gamma H \) is minimum value of \( G \) for which \( \phi = 0 \). For given \( G_{ao} \) the values of \( \hat{\delta}_h, x_{co}, \alpha_1 \) and \( \alpha_2 \) can be evaluated from the condition of continuity of heat flux (i.e. \( \partial \hat{G}/\partial x \)) at \( x=x_{co} \).

Calculated waveforms of current, voltage, axial value \( \hat{\delta}_c \) and radius of conductive core \( x_c \) are shown in Fig. 3 for the case near the boundary for thermal reignition of arc.

Fig. 4 presents the results in the Mayr's plot giving information about character of dynamic behaviour of the arc. The calculated curve is compared with the results of measurements on SF\(_6\) arc in the same electric circuit. It can be seen that observed typical rapid changes of relative derivative of conductivity in the vicinity of current zero can be properly described by the model.

References

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