MODELING OF THE TRANSPORT PHENOMENA
IN THE ANODE REGION OF HIGH CURRENT ARCS

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ABSTRACT

The transport phenomena in the anode region of wall stabilized high current D.C. arcs are described by differential conservation equations. Solutions are obtained for atmospheric pressure nitrogen and argon arcs. Considering the anode mechanism alone, the results indicate that nitrogen arcs tend to form constricted anode arc roots in contrast to argon arcs.

1. INTRODUCTION

For D.C. arcs in melting and remelting applications an improved knowledge of the heat flux from the arc to the melt is necessary. This heat transfer to the molten pool as the anode is strongly coupled with the transport of mass, momentum, and electric charge in the anode region.

As the technical situation in an arc furnace is too complex for a basic understanding of the interacting transport processes, experimental and theoretical investigations introduce a simplified arc model (1 - 3), which consists of a wall stabilized rotational symmetric D.C. arc operated between a hot cathode and a cooled anode. Nitrogen and argon are used as representative examples for plasma gases in technical applications.

This work considers atmospheric pressure arcs which are wall stabilized by a constrictor tube of approximately 20 cm length and 1 cm inside diameter. The constrictor and the anode are water cooled. The constrictor tube consists of single segments separated by gaps which reduce the pressure gradients between the arc column and the surroundings. In the configuration considered here the gap distance between the last constrictor segment and the anode is 2.5 mm.

The plasma flow in the arc is induced by the self-magnetic pumping effect in the electrode regions. Two different types of arc attachment have been observed in the anode region depending on the operation conditions (2). In the constricted attachment, cold gas enters the anode region from the side, whereas the
flow direction is opposite in case of a radial expansion of the arc in the gap between constrictor and anode. Eliminating the influence of the cathode jet, the model presented here describes the anode arc attachment affected by the anode mechanism alone.

2. MATHEMATICAL MODEL

The theoretical model is concerned with the flow-affected zone in the anode region of steady state, rotationally symmetric arcs under local thermal equilibrium (LTE) conditions. Deviations from LTE which may occur in a thin boundary layer have been studied separately (4) and are neglected here.

The problem can be described in cylindrical coordinates by a set of five coupled nonlinear differential equations (5). The momentum transfer is governed by the Navier-Stokes equations for the radial and the axial component of the plasma flow velocity including the Lorentz force due to the interaction of the electric current and the self-induced magnetic field. The equation of continuity describes the conservation of the mass flow. The energy equation includes the joule heating, the electron enthalpy transport, and the radiation losses. The electric current is governed by the electrical potential equation.

Taking the thermodynamic and transport properties for nitrogen and argon from the literature, the set of equations can be solved iteratively by a computer program using some boundary conditions which are derived from experimental results (5). In contrast to previous modeling work, no assumptions about induced gas flow rates are required, i.e. these gas flow rates are part of the solutions of the conservation equations.

3. RESULTS AND DISCUSSION

Assuming fully developed conditions in the arc column, the situation is essentially simplified to a one-dimensional problem, and the energy balance equation reduces to the Elenbaas-Heller equation for the radial temperature distribution. Figs. 1 and 2 show the results for nitrogen and argon arc columns of 5 mm radius at 250 A. In addition to the temperature profiles, the curves of the thermal conductivity are plotted in dashed lines. Due to the dissociation of the N2-molecules the thermal conductivity of nitrogen obtains a relative maximum near 7000 K followed by a minimum near 10000 K, which isolates the center part of the nitrogen arc column resulting in the formation of a hot core. In contrast, the argon thermal conductivity increases monotonically with temperature leading to a rather flat temperature profile with a steep gradient near the constrictor wall. Thus the thermal conductivity of the plasma gas strongly influences the temperature distribution and may affect the arc attachment shape in the anode region.
The calculated isotherms and the streamlines in the anode region of a nitrogen arc at 250 A are shown in Fig. 3. The arc forms a constricted attachment. The self-magnetic pumping effect draws in a mass flow rate of \(3.4 \times 10^{-5}\) kg/s. The temperature in the hot core in front of the anode reaches 21000 K exceeding the maximum temperature of the arc column. If the arc current is increased to 400 A the results remain similar with higher temperatures and an increased mass inflow from the side.

As Fig. 4 shows, the situation is completely different for an argon arc at 250 A. The relatively flat temperature profile expands into the gap between constrictor and anode. As a consequence, the self-magnetic pumping effect changes in direction and leads to an inflow of plasma from the arc column into the anode region. Thus a diffuse anode attachment is formed. The self-induced mass flow rate is \(2.2 \times 10^{-5}\) kg/s.

These different attachment modes are affected by the thermal conductivity of the plasma gas which influences the temperature field and, by that, determines the electric current distribution. Due to the thermal isolation of the hot core in the nitrogen arcs by a minimum of the nitrogen thermal conductivity, these arcs constrict in front of the cooled anode. The flat temperature profile of the argon arc with a relatively high temperature near the inner constrictor surface expands into the gap where the radial cooling effect of the constrictor tube is not efficient. The different tendencies of the arcs to constrict or to expand result in different directions of the plasma flow induced by the self-magnetic pumping effect, which, in turn, reinforces constrictions or expansion, respectively.

These theoretical results agree with experimental findings. It should be pointed out that they are limited to the parameters of the arc model considered here. For larger gaps between constrictor and anode different attachments have been observed in argon arcs with a radial expansion in the constrictor-near gap region and a constriction at the anode leading to an anode jet (3).

From the computed results for temperature and current density in the anode region the heat flow towards the anode can be evaluated. The heat transfer includes heat conduction, electron enthalpy transport, and radiation. The electron heat transfer is affected by the work function of the anode material, which is 4.7 eV for the copper anode used in the experimental setup. The calculations show that for the arcs under consideration, the main part of the transferred heat is carried by the electrons. Heat conduction contributes only about 10 percent to the total heat flux. The contribution of radiation is less than 5 percent due to the fact that only radiation emitted in the near anode region contributes to the anode heat flux; from the radiation emitted in the arc column only a small fraction due to the solid angle subtended is transferred to the arc attachment area.
Fig. 5 shows the calculated heat flux densities across the anode for a nitrogen and an argon arc at 250 A with only self-induced flow in the anode region and a gap distance of 2.5 mm between constrictor and anode. The constricted attachment of the nitrogen arc leads to a strongly peaked heat flux density, whereas for the diffuse argon arc attachment the heat flux distribution is rather uniform across the anode. The total anode heat flux is 2.2 kW for the nitrogen arc and 1.9 kW for the argon arc.

An efficiency $\eta$ can be defined relating the anode power to the total power input into the anode region. As a control volume a region adjacent to the anode surface is considered with a radius of 10 mm and an axial length of 14 mm. In the case of a constricted arc attachment, the power input consists of the joule heating and the electron enthalpy flow. In a diffuse arc attachment the hot plasma flow entering from the arc column is cooled in the anode region before it leaves the control volume, thus contributing additionally to the power input.

The results for the nitrogen arcs at 250 A and 400 A and for the argon arc at 250 A are listed in the following table. In addition, the corresponding values are given for a 250 A nitrogen arc with forced diffuse attachment by a superimposed plasma flow of $2 \times 10^{-5}$ kg/s directed towards the anode.

<table>
<thead>
<tr>
<th>Anode attachment</th>
<th>Total anode power</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$ 250 A</td>
<td>constricted</td>
<td>2.2 kW</td>
</tr>
<tr>
<td>N$_2$ 400 A</td>
<td>constricted</td>
<td>3.8 kW</td>
</tr>
<tr>
<td>Ar 250 A</td>
<td>diffuse</td>
<td>1.9 kW</td>
</tr>
<tr>
<td>N$_2$ 250 A</td>
<td>forced diffuse by superimposed flow ($\dot{M} = 2 \times 10^{-5}$ kg/s)</td>
<td>2.7 kW</td>
</tr>
</tbody>
</table>

For the constricted nitrogen arcs at 250 A and 400 A the relation between the corresponding power terms is nearly the same as the relation between the arc currents. The efficiencies are similar in both cases with $\eta = 29 \%$ for 250 A and $\eta = 30 \%$ for 400 A.

A considerably larger part of the power input is transferred to the anode in the arcs with diffuse attachments. The efficiency of the 250 A argon arc is $\eta = 41 \%$. The forced diffuse attachment of the 250 A nitrogen arc shows an efficiency of $\eta = 37 \%$ with the absolute anode power also exceeding that of the corresponding constricted attachment.

The analysis of the heat flux to the anode indicates that, with respect to technical applications, diffuse arc attachments are
advantageous rather than constricted attachments. In the diffuse arc attachments considered here the anode heat flux density is equalized across the anode surface, and a larger fraction of the power input is transferred to the anode compared to the constricted attachments.

ACKNOWLEDGEMENTS

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REFERENCES


![Fig. 1: Temperature and thermal conductivity in a nitrogen arc column at 250 A.](image1)

![Fig. 2: Temperature and thermal conductivity in an argon arc column at 250 A.](image2)
Fig. 3:
Isotherms (bold-type) and streamlines of a 250 A nitrogen arc.

Fig. 4:
Isotherms (bold-type) and streamlines of a 250 A argon arc.

Fig. 5:
Heat flux density to the anode.
Total heat flux: Nitrogen: 2.2 kW
Argon: 1.9 kW