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Numerical analysis of the influence of splitter-plate erosion on an air arc in the quenching chamber of a low-voltage circuit breaker

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Abstract
The influence of metal vapour on the arc behaviour during the arc-splitting process in the quenching chamber of a low-voltage circuit breaker is investigated numerically. A three-dimensional magnetohydrodynamic model of air arc plasma, taking into account the production of metal vapour from erosion of an iron splitter plate, is developed. An equation describing conservation of the iron vapour mass is added to the standard mass, momentum and energy conservation equations. The influence of the iron vapour on the thermodynamic and transport properties of the gas mixture is considered. The arc voltage, distributions of temperature, gas flow and mass fraction of iron vapour in the arc chamber are calculated. The formation of new arc roots on the splitter plate is examined. The simulation results indicate that this is strongly influenced by the presence of iron vapour from the splitter plate, due to the increased electrical conductivity in the arc root formation region. The consequences of this arc are dramatic. The presence of metal vapour causes the arc to attach first to the cathode side of the splitter plate, and electromagnetic forces then cause the arc on this side to move more rapidly than the arc on the anode side. The opposite occurs if metal vapour is neglected. High-speed photography of arc motion is used to confirm the arc motion predicted in the presence of metal vapour. Further, the calculated arc voltage taking into account metal vapour is lower than that calculated neglecting metal vapour, because of the increased electrical conductivity, and agrees much better with the measured voltage.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
The purpose of circuit breakers is to switch on and off operating or fault currents in electric circuits. Opening the contacts in a circuit breaker leads to the formation of an arc, and it is important that the arc be extinguished as rapidly as possible. Quenching chambers with splitter plates are the most effective and widely used method of arc extinction in low-voltage circuit breakers. After the contacts are opened, an electric arc runs along electrodes, and is subsequently divided into a series of short arcs by metal splitter plates. The arc voltage is increased by the introduction of multiple anode and cathode fall voltages, which promotes extinction of the arc [1–3].

The behaviour of the arc plasma is fundamental in determining the performance of the quenching chamber, and the arc-splitting process is one of the most important components of this behaviour. Furthermore, when the current is high and the arc remains within the splitter plates for a
sufficiently long time, the surfaces of the plates can reach the melting point of the metal. This leads inevitably to partial vaporization of the metal. Figure 1 shows a group of splitter plates in a low-voltage circuit breaker that have been strongly eroded by the high-temperature arc plasma after several openings (see the regions marked A and B). The splitter plates occupy the largest fraction of the volume of the quenching chamber, which means that the effect of metal vapour from these plates is more significant than that from the electrodes. Thus, investigations into the influence of metal vapour from erosion of the splitter plates during the arc-splitting process are important for the design of switching devices.

There have been a number of previous investigations of the influence of electrode erosion on thermal arc behaviour. For example, Gonzalez and Gleizes [4] modelled a short free-burning arc in argon at atmospheric pressure taking into account the evaporation of metal; this and other work on the effects of metal vapour in arc welding have been discussed by Murphy et al [5]. Zhang et al [6] investigated the influence of copper vapour from electrode evaporation on the behaviour of an SF$_6$ arc in a supersonic nozzle. Rong et al [7] studied the influence of copper vapour on low-voltage circuit breakers during the contact opening process.

Arc splitting is the most complex of the processes occurring in the circuit breaker, due to the complexity of the splitter-plate geometry in low-voltage switching devices, the nonlinear magnetic phenomena associated with ferromagnetic splitter plates, the vaporization of the splitter plates by the arc plasma and so on. Although there have been contributions to the study of arc splitting, e.g. [2, 3, 8], in which a thin layer of elements with a nonlinear current density–voltage characteristic surrounding the splitter plate was used to represent the formation of new arc roots, the influence of metal vapour during the arc-splitting process has not been studied. Further, the boundary regions between the arc and the anode, and the arc and the cathode, have been treated in the same way in previous studies, for simplicity.

This paper presents a study of arc behaviour in a low-voltage quenching chamber during the arc-splitting process, taking into account the influence of the vapour produced by erosion of an iron splitter plate. Iron is usually used in a low-voltage quenching chamber because of its ferromagnetic properties. Further, the anode and cathode boundary regions are treated differently. A three-dimensional mathematical model, including an equation for the conservation of mass of iron vapour, has been developed. The influence of the metal vapour on the thermodynamic and transport properties of the gas mixture is taken into account.

In section 2, a description of the mathematical model, including the equations for conservation of mass, momentum, energy and mass of metal vapour, is presented. The method of calculation of the thermodynamic and transport properties of the mixture of air and iron vapour is described in section 3. The computational results, including the distribution of arc temperature, current density and iron vapour concentration in the chamber, are presented and discussed in section 4. The influence of iron vapour on arc voltage and the formation of new arc roots on the splitter plate are also investigated in detail. Finally, in section 5, the results of experimental work carried out to test the validity of the simulations are presented and discussed.

2. Mathematical model

In the arc running and splitting process, electrode boundary layers effects play an important role in the formation of new arc roots, and contribute significantly to the total arc voltage. Without taking these effects into consideration, the bending of the arc column and its squeezing around the plate, which are important phenomena in the process, cannot be simulated [3]. The electrode boundary layers are usually divided into sheath, pre-sheath and so on. In this paper, we are not concerned with the detailed structure of the electrode boundary layer, and the term ‘sheath’ is used to refer to the entire electrode boundary layer. The sheath region is included in the calculation domain.

Figure 2 shows the geometry of the arc chamber adopted for the purposes of this study. This is a simplified version of a low-voltage circuit breaker, in particular, we use only one splitter plate. Figure 3 is a schematic diagram of the symmetry plane in figure 2. The calculation domain is divided into several regions: the arc column region, the solid metal region, which includes the electrodes and splitter plate, the anode and cathode-sheath regions surrounding the metal regions and an extended region for magnetic calculations. The regions are treated separately as described in the following subsections.
Figure 3. Regions on the symmetry plane (z = 0) in the calculation domain.

2.1. Arc column and sheath region

The arc model is based on magnetohydrodynamic (MHD) theory, and the plasma is assumed to be in local thermodynamic equilibrium (LTE) [9] and the flow is assumed to be laminar theory, and the plasma is assumed to be in local thermodynamic equilibrium (LTE) [9] and the flow is assumed to be laminar. The arc model is based on magnetohydrodynamic (MHD)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = S_m.$$  

(1)

(2) Momentum conservation equation:

$$\frac{\partial (\rho \vec{V})}{\partial t} + \nabla \cdot (\rho \vec{V} \vec{V}) = \nabla \cdot (\eta \nabla \vec{V}) - \frac{\partial \rho}{\partial x_i} + (\vec{J} \times \vec{B})_i.$$  

(2)

(3) Energy conservation equation:

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho H \vec{V}) = \nabla \cdot \left( \frac{\lambda}{c_p} \nabla H \right) + \sigma E^2 - q_{\text{rad}} + q_\eta + S_m h_i.$$  

(3)

In the above equations, $\rho$ is the density, $c_p$ is the specific heat, $\eta$ is the dynamic viscosity, $\lambda$ is the thermal conductivity, $\sigma$ is the electric conductivity, $\vec{J}$ is the current density, $\vec{B}$ is the magnetic flux density, $E$ is the electric field, $t$ is time, $p$ is the pressure, $T$ is the temperature, $H$ is the enthalpy, $q_\eta$ is the viscous dissipation and $S_m$ is the mass source term:

$$S_m = \begin{cases} m(\Delta S/\Delta V) & \text{sheath region,} \\ 0 & \text{arc coloumn region,} \end{cases}$$  

(4)

$$m = q_{\text{vap}} / h_v,$$  

(5)

$$q_{\text{rad}} = 4\pi \epsilon_{\text{N}},$$  

(6)

where $q_{\text{vap}}$ is the energy flux of the metal vapour as described later, $h_v$ is the sum of the latent heats of fusion and vaporization, $\Delta V$ is the grid volume adjacent to the eroded splitter plate and $\Delta S$ is the area of the surface grid. The initial momentum of metal vapour as it evaporates is ignored for simplicity. The radiation energy source term $q_{\text{rad}}$ is obtained using the net emission coefficient method, $\epsilon_N$ is the net emission coefficient [13, 14]. The energy source term associated with the injection of metal vapour involves the rate of vaporization of splitter plate $m$ and the equivalent total enthalpy of vapour entering the arc plasma $h_v$, which includes the iron vapour enthalpy and the energy input due to cathode electrons:

$$h_v = h_{\text{vap}} + |j_e| \frac{V_e}{m},$$  

(7)

where $h_{\text{vap}}$ is the iron vapour enthalpy at the boiling point, $j_e$ is the current density carried by electrons and $V_e$ is the voltage drop in the cathode sheath, as described later.

(4) The magnetic field and the electrical potential are calculated in the whole calculation domain. The vector potential method is adopted to calculate the electromagnetic field:

$$\vec{B} = \nabla \times \vec{A},$$  

(8)

$$\vec{E} = -\nabla \Phi,$$  

(9)

$$\nabla \cdot (\nabla \vec{A}) = -\mu \vec{J},$$  

(10)

$$\nabla \cdot (\sigma \nabla \Phi) = 0.$$  

(11)

In the above equations, $\vec{A}$ is the magnetic or vector potential and $\Phi$ is the electric potential. The constitutive relationships:

$$\vec{J} = \sigma \vec{E},$$  

(12)

$$\vec{B} = \mu \vec{H},$$  

(13)

are used. The nonlinear electrical conductivity of the plasma (see section 3) and the $B-H$ hysteresis curve of iron are used in the arc column region and the ferromagnetic splitter plate, respectively.

In the cathode-sheath region, the electrical conductivity is treated differently from the arc column so as to describe the arc root formation process. In the arc running and splitting process, the temperature of the metal surface outside the arc root spot is below the melting point, and if LTE is assumed, the adjacent gaseous regions are electrically insulating. However, in practice, non-equilibrium effects such as thermionic emission and ambipolar diffusion can make these regions highly conducting [15]. We use the effective electrical conductivity to account for these effects.

$$\sigma_{\text{eff}} = \frac{J \Delta y}{U_e},$$  

(14)

where $\Delta y = 0.1$ mm is the cathode-sheath thickness, which is the maximum experimentally observed thickness of the sheath region [6, 16], $J$ is the current density and $U_e$ is the potential drop in the cathode-sheath region. The appropriate value of $U_e$ for a non-thermionic cathode material such as iron, particularly in the presence of metal vapour, is not clear. We have chosen a value of 14.5 V for current densities greater than $10^8$ A m$^{-2}$. 


in accordance with measurements and calculations for non-
thermionic cathodes [6, 17, 18]. For lower current densities,
there is evidence that \( U_e \) is somewhat larger in circuit breaker
arcs [19], and we have chosen 22.6 V for the maximum voltage,
reached for current densities below \( 10^4 \) A m\(^{-2} \), on the basis of
the results given for thermionic cathodes in [20, 21].

The anode-sheath region is electrically conducting due to
the ambipolar diffusion of charged particles through the sheath
[22]. The investigation of Morrow and Lowke [22] has shown
that the anode-sheath thickness dominated by diffusion is
typically about 0.04 mm. In the electron-diffusion dominated
region, it is likely that the electric field at the anode surface is
negative [23, 24]. Rather than represent these complexities in
detail, we make our sheath mesh large enough (0.1 mm)
to extend across the diffusion-dominated region, and assume
that the effective electrical conductivity in the anode sheath is
equal to that of the arc column adjacent to the sheath. This
is in accordance with the LTE-diffusion model of Lowke and
Tanaka [25].

(5) Mass fraction equation:
The mixing of metal vapour in the mixture is determined
by convection and diffusion effects, and is described by the equation of
conservation of metal vapour mass:

\[
\frac{\partial (\rho c_m)}{\partial t} + \nabla \cdot (\rho c_m \vec{v}) - \nabla \cdot (\Gamma \nabla c_m) = 0, \tag{15}
\]

\[
c_m = \frac{m_m}{m_m + m_{air}} = \frac{n_m M_m}{n_m M_m + n_{air} M_{air}}, \tag{16}
\]

where \( \rho \) and \( \vec{v} \) are, respectively, the density and mass-average
velocity of the mixture. \( \Gamma_c \) is the diffusion coefficient, \( c_m \) is the
mass fraction of metal vapour in the mixture, \( m_m \) is the
mass of metal vapour, \( m_{air} \) is the mass of air, \( n_m \) and \( M_m \) are,
respectively, the molar number and molar mass of metal vapour and
\( n_{air} \) and \( M_{air} \) are, respectively, those of air.

2.2. Electrode region

The energy conservation equation is solved within the
electrode and splitter-plate regions. The Joule heating effect
is ignored as the electrical conductivity of the electrode and
splitter-plate regions. The Joule heating effect
is described by the energy conservation equation:

\[
\partial (\rho c_p T_m) + \nabla \cdot (\rho c_p \vec{v} T_m) - \nabla \cdot (k_m \nabla T_m) = 0, \tag{17}
\]

where \( \rho \), \( c_p \), \( k_m \) and \( T_m \) are, respectively, the density, the specific heat, the
temperature of the cathode material vaporization \( q_{vap} \) and
electron-emission cooling \( q_e \):

\[
q_{vap} + q_e + q_{con c} + q_{rad c} = q_{con arc} + q_{ion} + q_{rad arc}, \tag{18}
\]

where the conductive heat flux terms are given by

\[
q_{con arc} = -\lambda_a \frac{\partial T}{\partial y}, \tag{19}
\]

\[
q_{con c} = -\lambda_c \frac{\partial T}{\partial y}. \tag{20}
\]

Here \( \lambda_a \) is the thermal conductivity adjacent to the cathode
surface and \( \lambda_c \) is the thermal conductivity of cathode. Since
the temperature of the cathode spot is low, radiation from the
electrode surface is negligible. Heating of the electrode by
radiation from the arc can also be neglected in comparison with
the other energy fluxes [22]. The ion bombardment heating is given by

\[
q_{ion} = j_i \left( V_c + \Phi_e + \frac{5k_B}{2e} T_c \right), \tag{21}
\]

where \( j_i \) is the ion current, \( V_c = 14.5 \) V is the voltage drop in
the cathode sheath [17]. \( \Phi_e \) is the work function of the cathode
material, \( V_i = 7.9 \) V is the ionization energy of the plasma
gas [26], \( k_B \) is Boltzmann’s constant, \( e \) is the magnitude of the
electronic charge and \( T_c \) is the cathode spot temperature.

Energy is carried away from the cathode surface by
electron emission.

\[
q_e = |j_e| \Phi_e, \tag{22}
\]

where \( j_e \) is the current density carried by electrons. The total
current density is \( |J| = j_i + j_e \). We use the approximation
\( j_e/|J| = 0.78 \) [6, 18].
After the cathode surface has reached its melting temperature, any additional incident energy is used to change the metal into liquid and then to vapour. The rate of the vaporization $m$ is obtained from

$$q_{\text{vap}} = h_v m,$$

(23)

where $h_v$ is the sum of latent heat of fusion and vaporization.

Outside the cathode spot region, the electrode exchanges energy with the gas through thermal conduction only.

### 2.4.3. Anode surface effects.

Similarly to the situation for the cathode, the iron evaporation rate at the anode can be calculated using the energy balance equation at the anode surface:

$$q_{\text{con a}} + q_{\text{rad arc}} + q_{\text{i e}} = q_{\text{con a}} + q_{\text{rad a}} + q_{\text{vap}}.$$  

(24)

The radiation terms $q_{\text{rad arc}}$ and $q_{\text{rad a}}$ are ignored for the same reason mentioned previously for the cathode surface. The conduction terms $q_{\text{con arc}}$ and $q_{\text{con a}}$ are calculated in the same manner as those for the cathode surface; see (19) and (20).

In the above equations, $q_{\text{i e}}$ is the energy associated with electron capture, and is given by

$$q_{\text{i e}} = \left| j_\text{n} \right| \left[ \Phi_a + V_a + \frac{5k_B}{2e} \left(T_g - T_a\right) \right],$$

(25)

where $j_\text{n}$ is the current density component perpendicular to the anode surface, $T_a$ is the anode surface temperature, $T_g$ is the gas temperature just in front of the anode spot, $V_a$ is the anode fall (assumed to be 2.1 V) [18] and $\Phi_a$ is the work function of the anode material (4.5 V).

### 2.4.4. External boundary conditions.

The external boundary is the boundary of the whole calculation domain. The temperature boundary condition is described by the heat flux associated with the conduction of the sidewalls and electrodes [13]. Vents 1 and 2 are used to connect the inner air volume with the atmosphere outside the chamber, and the static gauge pressure is set to zero. The Dirichlet condition of zero electric potential is imposed on the cathode as the electric field boundary condition.

During the simulation, a uniform current density distribution $j$ is fed into the plasma from the current inlet, as shown in figure 2.

### 3. Calculation of thermodynamic properties and transport coefficients of air-iron mixture

The plasma is assumed to be in LTE. The thermodynamic properties (density, specific heat and enthalpy) were calculated for a chemical equilibrium composition, obtained using minimization of the Gibbs energy. The following species were considered: $\text{N}_2$, $\text{N}_2^+$, $\text{N}$, $\text{N}^+$, $\text{N}_3^+$, $\text{N}_3^+$, $\text{O}_2$, $\text{O}_2^+$, $\text{O}$, $\text{O}^+$, $\text{O}^{2+}$, $\text{O}^{3+}$, $\text{O}^{4+}$, $\text{N}_2\text{O}$, $\text{N}_2\text{O}^+$, $\text{NO}$, $\text{NO}^+$, $\text{NO}_2$, $\text{NO}_2^+$, $\text{Ar}$, $\text{Ar}^+$, $\text{Ar}^{2+}$, $\text{Ar}^{3+}$, $\text{Ar}^{4+}$, $\text{C}$, $\text{C}_2$, $\text{C}_3$, $\text{C}_4$, $\text{C}_5$, $\text{C}_6$, $\text{C}_2^+$, $\text{C}_3^+$, $\text{CN}$, $\text{CO}$, $\text{CO}_2$, $\text{Fe}$, $\text{Fe}^+$, $\text{Fe}^{2+}$, $\text{Fe}^{3+}$, $\text{Fe}^{4+}$ and $e^-$. The thermodynamic properties of the monatomic species were calculated using the atomic transitions listed by Moore [29, 30]. The thermodynamic properties of the molecular species were taken from the JANAF tables [31]; where necessary, the properties were extended to temperatures above 6000 K using molecular spectral data.

The transport properties, including the combined diffusion coefficients, were calculated using the Chapman–Enskog method [32, 33]. The required collision integrals for interactions between air species were calculated using the methods given by Murphy and Arundell [34] and Murphy [35]. The collision integrals for Fe–Fe interactions were obtained using the Lennard–Jones (12,6) potential, and those for $X$–Fe by interpolating between the $X$–$X$ and Fe–Fe collision integrals, using the method given in [36] (note that $X$ represents any atomic species other than Fe). The collision integrals for $X$–Fe$^+$ and Fe–$X^+$ interactions were calculated using the polarization potential, and for those for Fe–Fe$^+$ interactions using a combination of the charge exchange parameters determined from the work of Rapp and Francis [37] and the polarization potential. All collision integrals for interactions between charged species were determined using the shielded Coulomb potential. Relevant details and references are given in [34]. The $e^-$–Fe collision integrals were determined by integrating the momentum transfer cross-section, which was obtained using the effective radius approximation for low collision energies, and the classical approximations for high collision energies [38].

The diffusion coefficient $\Gamma_v$ used in (15) is the combined ordinary diffusion coefficient [39], calculated for mixtures of air and iron vapour. The combined temperature diffusion coefficient has been neglected. This approach was found to give a fair approximation for the diffusion mass flux of copper vapour in an argon plasma in [40]. Since air is not a homonuclear gas, there is already an approximation inherent in applying the combined diffusion coefficient method for the air–iron–vapour mixture [35].

The densities, thermal conductivities and electrical conductivities for different mass fractions of iron vapour are compared in figures 4–6, respectively.

### 4. Simulation results

For the simulations in this paper, the coupled solver of Fluent is used and the numerical scheme is implicit in time with the time step size set to 2 $\mu$s. Arc ignition is not included in the simulation, and the calculation begins with a stationary temperature distribution between two electrodes without metal evaporation [2]. The energy balance at the electrodes is considered. The arc current value used in the calculation is derived from the experimental data shown in figure 17.

#### 4.1. Arc characteristics during the splitting process taking into account metal plate erosion

Temperature distribution sequences of the arc plasma during the splitting process are presented in figure 7. Figure 8 shows the mass fraction distribution of iron vapour at some of the same times.
Figure 4. Density versus temperature for air–iron-vapour mixtures at 1 atm. The percentages are mass percentages.

Figure 5. Thermal conductivity versus temperature for air–iron-vapour mixtures at 1 atm. The percentages are mass percentages.

From \( t \approx 0.1 \) to 0.5 ms, the arc begins to expand and move along the electrodes under the influence of the Lorentz force and gas flow. As the gas flow velocity gradually increases due to the increasing current and the attraction of the arc to the ferromagnetic plate, an obvious elongation of arc column occurs in the direction of the splitter plate.

As discussed in sections 2.4.2 and 2.4.3, the internal boundary conditions between the arc column and the anode and cathode are treated differently. At \( t = 0.586 \) ms, the anode arc root has clearly moved further than the cathode arc root. The phenomenon can also be seen in the experiment results shown in figures 15 and 16.

Figure 9 shows the flow velocity field at two times. It is notable that a circular vortex emerges ahead of the cathode arc root in figure 9(a). The flow direction is mainly towards the upper region, which leads to hot gas being transported away from the region ahead of the cathode arc root. This means the electrical conductivity of the region is relatively low, and thus the progress of the cathode arc root is slowed down in this phase.

When \( t > 0.7 \) ms, that is after the leading edge of the arc column reaches the splitter plate, the arc is elongated...
continuously due to the effects of gas flow and ferromagnetic plate attraction. In this phase, the gas flow velocity near the arc roots increases and is mainly in the horizontal direction, as shown in figure 9(b). This increases the heating of the air in front of both arc roots, which in turn increases the electrical conductivity in these regions, and the cathode arc root is able to catch up with the anode arc root in this phase.

Subsequently, as the arc roots moving along the electrode surfaces, the arc column gradually bends and stretches due to the blocking effect of the relative cold splitter plate. At $t = 1.086$ ms, the high-temperature region of the plasma has entered the two gaps between the electrodes and the plate. As the arc column energy is transported to the splitter plate, the iron plate begins to vaporize, as shown in figure 8. At this stage, most of the arc current still flows outside the splitter plate, as shown in figure 10(a).

For $t > 1.2$ ms, two new arc roots have formed on the surface of splitter plate. The current density in the plate increases rapidly, as shown in figure 10(b). In this phase, the vaporization of the splitter plate becomes increasingly intense, as shown in figure 8. The iron vapour is concentrated in the region near the arc root, and moves forward with the arc column because of the strong convective flow.

The production of metal vapour in the cathode spot region on the splitter plate is stronger than in the anode spot region. This is because the current density, and therefore the energy density, is higher. This in turn increases the electrical conductivity in this region, since the electrical conductivity of iron vapour is much higher than that of air for temperatures below about 15 000 K (see figure 6). The arc root therefore moves more rapidly onto the cathode (upper) side of the splitter plate than on the anode (lower) side.

For later times, the arc column is divided into two separate parts, which are completely confined to the gaps on either side of the splitter plate. In this phase, the lower arc moves more slowly than the upper arc. This is because of the influence of the magnetic field induced by the current in the splitter plate. Since the upper arc leads the lower arc, the current in the splitter plate flows from right to left (for the geometry shown in figure 3). This can already be seen in figure 10(b). The magnetic field is therefore directed out of the page below the splitter plate, so the Lorentz force opposes the arc motion in this region. Similarly, the magnetic field is directed into the page above the splitter plate, and the Lorentz force accelerates the arc motion here.

4.2. Influence of metal vapour on arc characteristics during the splitting process

The influence of metal vapour from splitter-plate erosion on the displacement of the arc roots is shown in figures 11 and 12; the figures, respectively, show the results obtained with and without account being taken of the production of metal vapour. The results are shown as a function of time, relative to $x = 0$ mm, which is the position at which arc ignition occurs. Curves a1 and c1 are, respectively, the calculated arc root displacements of the anode and cathode considering erosion. Curves sa1 and sc1 are the displacements of anode and cathode arc roots on the splitter plate, in the simulation considering erosion. Curves a2, c2, sa2 and sc2, respectively, have the same meaning but are calculated neglecting erosion.

In the initial stage of arc motion, the arc roots have not reached the splitter plates, so curves sa1, sc1, sa2 and sa2 are set to zero. Before the splitting process, the arc root displacements have the same features in the two cases, since the erosion of the electrodes is not included in the simulation. We note that the anode arc root moves in front of the cathode arc root; this effect can occur in our simulations because of the different mathematical descriptions of the two sheath regions.
Figure 10. Arc current density distribution on the symmetry plane. (a) \( t = 1.086 \text{ ms} \) (b) \( t = 1.356 \text{ ms} \). The maximum current density is \( 1.1 \times 10^8 \text{ A m}^{-2} \), marked D in (b) is the isoline of current density \( 10^7 \text{ A m}^{-2} \).

Figure 11. Time dependence of the arc root displacement, taking into account the influence of metal vapour from splitter-plate erosion, for the anode and cathode roots on the electrodes, and the anode and cathode roots on the splitter plate.

When \( t \approx t_1 \) in figure 11, the arc column makes contact with the splitter plate and starts to become elongated, and the current density in the splitter plate increases above zero. The arc root displacements at this time are near 0.03 m, where \( x = 0.03 \text{ m} \) corresponds to the edge of the splitter plate. When \( t > t_2 \), the new arc root has clearly begun to form on the splitter plate. From the curves in figure 11, the upper short arc, with arc roots on the anode and the splitter plate cathode, moves faster, eventually leading the lower short arc by more than 10 mm. However, when the erosion of the splitter plate is neglected, as in figure 12, the opposite results are obtained. The lower short arc moves faster and the upper short arc remains almost stationary in the chamber.

This very significant difference can be explained by the influence of the iron vapour on the electrical conductivity of the plasma in the region in which the new arc root is formed on the splitter plate. If erosion is neglected, the anode arc root on the lower side of the splitter plate forms more easily than the cathode arc root on the upper side of the plate. The lower arc is therefore formed more rapidly, and leads the upper arc. The current in the splitter plate flows from left to right, and the magnetic field is out of the page. The Lorentz force therefore retards the motion of the upper arc and accelerates the motion of the upper arc. If erosion is taken into account, however, the metal vapour is preferentially produced from the upper side of the splitter plate due to the higher current density in the cathode arc root, as discussed in section 4.1. The upper arc is then formed more rapidly due to the increased electrical conductivity, and leads the lower arc, reversing the direction of the current in the splitter plate, of the induced magnetic field and of the resulting Lorentz forces.

The time dependence of the arc voltage is compared for the calculations taking into account (v1) and neglecting splitter-plate erosion (v2) in figure 13. Before arc splitting occurs, the voltages are the same, since no metal vapour is produced. For times greater than \( t \approx 1.1 \text{ ms} \), the arc voltage is smaller when erosion is considered. This is because the metal vapour from the splitter increases the electrical conductivity of the plasma.
and surrounding hot gas at temperatures below 15 000 K, and most of the region is at such temperatures.

5. Experimental results

The objective of the experiment described here is to obtain information about the arc behaviour in the arc chamber and during the splitting process, with which to compare the predictions of the simulations. A simplified arc chamber was designed that corresponds to that used for the simulations, shown in figure 2. It consists of two arc runners and one iron splitter plate, and has insulated walls. One of the walls is made of transparent materials in order to allow the arc behaviour to be recorded by a high-speed camera.

Figure 14 shows the arrangement of the experimental apparatus. The test object (the arc chamber) is connected to the oscillating circuit. Arc voltage was measured by a Tektronix P6015 high-voltage probe and the current is measured by a Hall sensor. The experimental waveforms were recorded by a Tektronix TDS460A oscilloscope.

The images recorded by a high-speed camera during the arc-splitting process are shown in figure 15. After the arc is ignited in the chamber, it begins to move forward towards the splitter plate. The anode arc root on the upper arc runner appears less concentrated and moves faster than the cathode arc root. Once the arc reaches the splitter, it is clearly apparent that the cathode arc root on the upper surface of the splitter plate moves ahead of the anode arc root on the lower surface of the plate, and that the upper arc subsequently moves more quickly than the lower arc ahead of the other one. These features have been identified in the results of the simulation when splitter-plate erosion was taken into account.

Figure 15. Images of the arc before and during the splitting process recorded by a high-speed camera

The arc root displacements taken from the measurements are compared with those from the simulations in figure 16. For $t < 0.94$ ms, the measurements indicate that the anode arc root moves ahead of the cathode root. After splitting occurs, the motion of all four arc roots is depicted in the figure. It is clear that the measured displacements show the same trends as the predictions of the simulations. In particular, the displacements of the lower arc (cathode and splitter-plate anode) roots agree closely. The measured displacements of the upper arc (anode and splitter-plate cathode) roots do not agree as well for the
duration of the arc motion, but nevertheless both the measured and calculated displacements are larger than for the lower arc roots.

The measured arc voltage is compared in figure 17 with that predicted by the numerical simulation taking into account splitter-plate erosion. The trends are again very similar. It should be noted, however, that in the initial period, the measured voltage is about 10 V lower than the calculated voltage. This is most likely due to the neglect of electrode erosion in the simulation; metal vapour from the electrodes will increase the electrical conductivity of the arc plasma, and therefore decrease the voltage. Once the arc-splitting process commences, the agreement between the measured and calculated voltages improves. Comparison with figure 13 indicates that the calculated voltage agrees much more closely with the measured voltage when splitter-plate erosion is taken into account.

The generally good agreement with experiment is encouraging, and indicates that the methods used for arc simulation in this paper are suitable to study the behaviour of the arc plasma in the arc-splitting process. We plan in future work to apply the model to simulate the arc behaviour in a more realistic low-voltage arc chamber with multiple splitter plates. In this case, the production of metal vapour from splitter-plate erosion will dominate that from electrode erosion.

6. Conclusions

A three-dimensional numerical model of the air arc in a low-voltage quenching chamber, which takes into account the production of metal vapour due to erosion of the splitter plate during the arc-splitting process, has been developed. An equation for the conservation of the mass of iron vapour was included to allow the iron vapour concentration to be determined, and the influence of the iron vapour on the thermodynamic and transport properties of the gas mixture was taken into account.

An important aspect of the model is that it incorporates different treatments of the arc attachment to the anode and cathode. This allows the different speeds of the arc roots on the anode and cathode to be simulated. This is critical in allowing the strong influence of metal vapour to be predicted.

Our simulations predict that the metal vapour produced by splitter-plate erosion has a major influence on the motion of the arcs formed in the splitter-plate region. When the influence of metal vapour is taken into account, the arc on the cathode side of the splitter plate moves more rapidly than the arc on the anode side. If metal vapour is neglected, the opposite behaviour occurs.

The current density in the cathode arc root is larger than that in the anode arc root, and therefore the vaporization rate is larger on the cathode side of the splitter plate. The presence of metal vapour increases the electrical conductivity of the plasma, which causes the arc to attach to the cathode side of the splitter plate first. If metal vapour is neglected, the arc attaches first to the anode side.

The relative motion of the arcs on the two sides of the splitter plate is then determined by the magnetic field induced by the current flowing in the splitter plate. The leading arc is accelerated, and the trailing arc retarded, by the Lorentz force. Thus, when metal vapour is taken into account, the arc on the cathode side of the splitter plate moves more rapidly than the arc on the anode side, while when metal vapour is neglected, it moves more slowly.

Measurements of the motion of the arcs using high-speed photography, and of the arc voltage, show good agreement with those predicted by the simulations taking into account metal vapour. In particular, the measurements show that the arc on the cathode side of the splitter plate moves more rapidly than the arc on the anode side. This indicates that the computational model includes the most important factors governing the arc motion, and that the differences in anode and cathode attachment behaviour are captured adequately.

The most critical contribution of the iron vapour is to increase the electrical conductivity of the plasma at temperatures up to 15 000 K. The simulation predicts that this has two consequences, both of which are supported by...
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