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The Gas Dynamics of Current-Limiting Devices During Immobility Time

Willem F. H. Merck and Valeri N. Zatelepin

Abstract—The aim of this paper is to extend our knowledge about the gas-dynamic processes in arcs during immobility time. For this purpose, the conservation equations in magnetohydrodynamic approximation were coupled with the thermochemical and Maxwell equations. Special features are the introduction of dissociation and ionization of nitrogen and oxygen, and the simultaneous calculation of the distributions of current density and magnetic induction in the arc. Numerical calculations were performed with a reduced two-dimensional (2-D) time-dependent model. Results of the calculations were compared with measurements. The development in time of the measured and calculated arc voltage and arc chamber pressure show very good agreement. The pumping effect of the double vortex in the arc region was confirmed by optical measurements. It is concluded that the three-layer model is a good representation for the main physical features during the immobility time, and that the presence of highly conducting gas in the downstream region of the arc is essential for its downstream movement.

Index Terms—AC circuit breakers, arc discharges, electromagnetic analyses, FDTD methods, fluid flow, gas discharges, MHD.

I. INTRODUCTION

THE electrical arc in current-limiting devices (CLD's) is situated in a self-induced magnetic field formed by the arc and the external leads. The influence of the Lorentz force and Joule dissipation in the nonsymmetrical magnetic field forces the arc into the zone of the extinction plates, where the arc extinguishes and the current is interrupted.

Experimental observations of the emission zone location, during initiation of the discharge, show that during some initial period (immobility time), the arc stays immobile. During this immobility time, many complex processes take place: the explosive creation of the arc when the contacts are at the instant of separation (Holmes [1]), and the production of plasma jets from the anode and cathode where electrode material is blown into the arc volume (Raizer [2]). The arc footpoints stay immobile between the separating contacts for about 1 ms, after which they start to move. During the immobility time, the electromagnetic forces act on the gas mixture inside the arc, initiating a double vortex which moves the hot gases toward the arc chamber. The aim of this paper is to describe the magnetogas-dynamic part of the processes

Fig. 1. Schematic view of the current-limiting device SBE-63. Calculations are performed in the XZ plane of symmetry.

during the immobility time. Fig. 1 gives a simplified view of the CLD for which calculations will be carried out in the plane of symmetry, the XZ plane, with the assumption that all quantities may be considered constant over the Y direction.

In the following sections, the theoretical model will be described, some indications will be given about the quasi-two-dimensional time-dependent numerical procedures, and finally, the computational results will be compared with experimental data.

II. MATHEMATICAL MODEL OF PROCESSES

The gas-dynamic behavior is described by the full system of conservation equations with the electromagnetic terms in MHD approximation (Mitchner and Kruger [3])

$$\begin{aligned} \frac{\partial}{\partial t} \begin{bmatrix} \rho \\ \rho \bar{u} \\ \rho \epsilon \end{bmatrix} + \nabla \cdot \begin{bmatrix} \rho \bar{u} \\ \rho \bar{u} \otimes \bar{u} + p \bar{I} - \bar{\tau} \\ \rho \bar{u} (\epsilon + \frac{p}{\rho}) - \lambda \nabla T - \bar{\tau} \cdot \bar{u} \end{bmatrix} \\ = \begin{bmatrix} 0 \\ \bar{J} \times \bar{B} \\ \bar{E} \cdot \bar{J} + q \end{bmatrix} \end{aligned} \quad (1)$$

where ρ = mass density, u = velocity vector = (u, v, w) , p = static pressure, I = unit tensor, τ = shear stress tensor, $\epsilon = e + u^2/2$, e = internal energy, λ = heat conduction coefficient, T = static temperature, J = current density, B = magnetic induction, E = electric field, and q = radiation losses.

Further physical processes taken into account are the change of current through the CLD and arc length because of the

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gap growth between contacts, the processes of dissociation and ionization, the diffusive and convective transfer of plasma components, the generation of electromagnetic field in the conductive medium, next to and inside the arc, and the erosion of electrodes.

Instead of a full nonstationary two-dimensional (2D-t) model on a fine grid, a more simple quasi-2D-t model will be used.

A. Gas Dynamics

The detailed description of the quasi-2D-t model used here for the calculations of gas-dynamic field quantities like axial velocity u , total density ρ , and total pressure P can be found in Zatelepin [4]. The calculations are performed in the XZ plane (see Fig. 2), which is divided into three layers: a central one and two adjacent to the walls. Quantities will be assigned with index 1 for the central layer and index 2 for the wall layers. Symmetry with respect to the X axis is assumed. The equations of mass, momentum, and energy transport for layers 1 and 2, averaged along the Y axis from the upper to lower electrode wall, yield

$$\frac{\partial(\rho S)_j}{\partial t} + \frac{\partial(\rho u S)_j}{\partial x} = Q_{rj} + Q_{rej} \quad (2)$$

$$\frac{\partial}{\partial t}(\rho u S)_j + \frac{\partial(\rho u^2 + p)(S)_j}{\partial x} = F_{aj} + F_{pj} + F_{frj} + Q_{mj} + Q_{mej} \quad (3)$$

$$\frac{\partial(\rho \epsilon S)_j}{\partial t} + \frac{\partial(\rho u H_o S)_j}{\partial x} = Q_{cond,xj} + Q_{cond,zj} + Q_{conv,zj} + Q_{radj} + Q_{ej} + Q_{eej} \quad (4)$$

where $j = 1, 2$.

The left-hand side terms in (2)–(4) are standard; on the right-hand side, we have: Q_{rj} , Q_{mj} , Q_{ej} are the exchange of mass, momentum, and enthalpy, respectively, between layers 1 and 2; $F_{aj} = JBS_j$ is the Lorentz force in layer j ; $F_{pj} = p_j dS_j/dx$ is the term which is connected to the divergence of the channel along the Y axis and the corresponding change of the layer cross section S_j ; F_{frj} is the friction force in layer j ; $Q_{cond,xj}$, $Q_{cond,zj}$, $Q_{conv,zj}$ are the conductive enthalpy transfer along the X and Z direction and the convective energy transfer in the Z direction, respectively; Q_{radj} is the radiative energy transfer; $Q_{ej} = JES_j$ is the electrical power input in layer j ; and Q_{rej} , Q_{mej} , Q_{eej} are the mass, momentum, and enthalpy sources because of the erosion of the electrode material.

B. Thermochemical Model

In Burt [5], the ideal gas model was used to connect the thermal and calorimetric quantities. Temperatures from 50 000 to 70 000 K in the arc zone were obtained. This proves the necessity to take the dissociation and ionization processes into account. At these temperatures, the degree of ionization reaches 1, and it is necessary to take the electron component in the pressure into account. The medium is atmospheric air,

so the following seven species, index “ i ,” were considered: N_2 , N , N^+ , O_2 , O , O^+ , and electrons “ e .”

It is assumed that chemical equilibrium exists at every time level. From the tables of Burhorn and Wienecke [6], it was found that NO molecules are mainly present in a small temperature interval around 3000 K at a concentration level below 7%. For the temperature range of the arc discharge, namely, 10 000–20 000 K, the NO molecules can be completely neglected. Double-ionized particles can be neglected too because their concentration is still below 0.1% at 20 000 K. Although Cu and Cu^+ play an important role during the initiation of the arc, Abdelhakim [7] showed that above 10 000 K, the ionization of Cu has a negligible contribution to the overall electrical conductivity of arcs in air.

The concentrations (n) of molecules, atoms, and ions are found from the Saha equations in the following simplified form:

$$\begin{aligned} \frac{n_O^2}{n_{O_2}} &= K_1; & \frac{n_N^2}{n_{N_2}} &= K_2; \\ \frac{n_O}{n_e n_{O^+}} &= K_3; & \frac{n_N}{n_e n_{N^+}} &= K_4. \end{aligned} \quad (5)$$

The Saha coefficients K_1 – K_4 are approximated as functions of the temperature T according to Gurwitsch [8]. Assuming charge neutrality yields

$$n_e = n_{N^+} + n_{O^+}. \quad (6)$$

The composition of air is taken to be 21 mol-% of oxygen and 79 mol-% of nitrogen, yielding

$$\frac{n_{O_2} + 0.5(n_O + n_{O^+})}{n_{N_2} + 0.5(n_N + n_{N^+})} = \frac{21}{79}. \quad (7)$$

Finally, we can write for the mass density of oxygen

$$m_{O_2}(n_{O_2} + 0.5(n_{O^+} + n_O)) = 0.23\rho. \quad (8)$$

In order to calculate the partial pressure of a component p_i , the total pressure of plasma p and the total enthalpy of the mixture H , the following equations have been used:

$$p_i = n_i kT; \quad p = \sum_{i=1}^7 p_i \quad (9)$$

$$H = \frac{\sum_{i=1}^7 p_i \mu_i h_i}{\sum_{i=1}^7 p_i \mu_i} \quad (10)$$

where i = index from 1 to 7 for the different components of the mixture, p_i = partial pressure, k = Boltzmann's constant, μ_i = molecular weight, h_i = enthalpy of 1 kg, approximated as a function of temperature according to [8], and m_{O_2} = molecular weight of O_2 molecule.

C. Electromagnetic Fields

In order to calculate the arc voltage, the distribution of the current density J , the electric field E , the magnetic induction B , the Lorentz force F_{aj} , and the electromagnetic power Q_{ej} , Maxwell's equations and Ohm's law are used. Further, based on the experimental fact that the arc is in a fixed position, the following basic assumptions are made: the electric field

Fig. 2. Region of calculations. The half-plane XZ is divided in a central region with an arc between x_1 and x_2 and a wall region without an arc. Exchange of matter, momentum, and energy between the two regions is considered. The X axis is the axis of symmetry.

Fig. 3. Simplified current loop for calculation of the magnetic induction component B_z . Biot-Savart's law is applied to the "closed circuit" a-b-c-d-e-f, yielding the matrix component B_{ij} of the induction B_{zi} .

E is constant in the arc zone, and is a function of time only, and has a component in the Y direction; the integral value of the current I is given at every moment of time; the zone where the current flows is limited and fixed in space; the current density has a component in the Y direction only and is independent of Z ; charge neutrality exists everywhere; the Hall effect can be neglected; the magnetic induction has a component in the Z direction only; the arc plasma can be approximated by a fully ionized gas; and all parameters are independent of Y . According to these assumptions, Maxwell equations and Ohm's law have been reduced to

$$\nabla \times B = \mu_0 J \quad (11)$$

$$J_y = \sigma(E_y - uB_z) \quad (12)$$

whereas J_y should match the measured value of the total current I through

$$I = \int J_y dx dz = h_z \int J_y dx \quad (13)$$

where h_z is the dimension of the arc in the Z direction.

The current distribution J can be expressed in a closed form, and the electromagnetic fields E and B can be derived directly from the J distribution. The configuration of Fig. 3 is considered.

For the interaction of the electromagnetic and the gas-dynamic fields, only the volume where $J > 0$ is of interest. The arc is situated in a fixed position between points x_1 and x_2 , and inside the central region $-0.5h_z < z < 0.5h_z$, and extends in the Y direction between the separating contacts. This arc region is divided in the X direction in $n (= 10)$ equal steps. The current leads abc and def have no resistance, and their cross section is negligible. The magnetic induction in cell i , caused by the current through cell j , $B(i, j)$, can be found

by applying Biot-Savart's law on the current loop abcdef

$$B_{ij} = \frac{\mu_0}{4\pi} h_z J_j \Delta x_j \oint_A \frac{dl \times r}{r^3}. \quad (14)$$

Defining

$$b_{ij} = \frac{\mu_0}{4\pi} \oint_A \frac{dl \times r}{r^3} \quad (15)$$

we find for the magnetic induction in any position x

$$B_i = h_z \sum_{n=1}^{10} J_j b_{ij} \Delta x_j. \quad (16)$$

The total current is now expressed as

$$I = h_z \sum_{j=1}^{10} J_j \Delta x_j. \quad (17)$$

Using Ohm's law (12), the total current can now easily be written as

$$I = h_z \sum_{i=1}^{10} (\sigma_i \Delta x_i) E - h_z \sum_{j=1}^{10} \left\{ (J_j \Delta x_j) \sum_{i=1}^{10} \sigma_i u_i b_{ij} \Delta x_i \right\}. \quad (18)$$

Introducing

$$b_{1j} = \sum_{i=1}^{10} \sigma_i u_i b_{ij} \Delta x_i \quad (19)$$

and

$$S_\sigma = h_z \sum_{i=1}^{10} \sigma_i \Delta x_i \quad (20)$$

we find straightforwardly for the electric field

$$E = \frac{I + \sum_{j=1}^{10} J_j b_{1j} \Delta x_j}{S_\sigma} \quad (21)$$

and for the current density

$$J_j = A_{ij}^{-1} \frac{\sigma_i I}{S_\sigma} \quad (22)$$

where

$$A_{ij} = \delta_{ij} - \frac{\sigma_i}{S_\sigma} b_{1j} \Delta x_j + h_z \sigma_i u_i b_{ij} \Delta x_j \quad (23)$$

and δ_{ij} is the unit tensor.

The terms F_{aj} and Q_{ej} are found from the following equations:

$$\begin{aligned} F_{a1} &= J(x) B(x) h_z \Delta y, & F_{a2} &= 0 \\ Q_{e1} &= J(x) E h_z \Delta y, & Q_{e2} &= 0 \end{aligned}$$

where h_z is the width of zone 1 and Δy is the distance between the movable contacts.

III. COMPUTATIONAL ASPECTS

For the calculations, the total length of the CLD (82 mm) is split into 70 cells, where the arc region has ten cells. The width of the central layer is 0.6 times the total width of 10 mm.

In the computations, the convective processes are calculated first, according to Godunov [9], with second-order spatial accuracy. The time step is determined by the Courant number 0.9. This initial solution is used to calculate the electromagnetic terms and other terms on the RHS of (2)–(4). This procedure is repeated until good convergence is obtained [4]. For both end walls, atmospheric conditions were taken ($p = 1$ atm, $T = 300$ K), and the walls are 50% open. The temperature of the side walls is kept at $T = 300$ K.

The main variables in the gas-dynamic part are the density and enthalpy, whereas in the thermochemical part, they are density and temperature. Iterations between the two solutions were performed within 10 K accuracy.

Viscosity and thermal conductivity were introduced according to Kalikhman [10]. Radiation losses were calculated according to the theoretical work of Hermann [11]. The electrical conductivity is found from

$$\sigma(T) = \frac{\text{const} \times n_e}{\sum \nu_{ei}} \quad (24)$$

where n_e = electron density, and ν_{ei} = cross section of the electron–plasma component collisions, with a maximum value of 10^6 S/m.

IV. EXPERIMENTS

The experiments were performed in a CLD specially designed for research purposes, derived from a commercial type, which has a nominal current of 63 A and can switch off prospective short-circuit currents up to 10 kA. The CLD is equipped with a pressure probe in a side wall of the arc chamber 30 mm downstream of the arc position. During the experiments, the current through and the voltage across the CLD were measured together with the static pressure in the arc chamber. Fig. 4 shows the measured data as a function of time. The arc voltage starts to increase after 0.4 ms, due to arc lengthening. After 0.6 ms the fluctuating arc voltage indicates the commutation of the arc from the upward moving contact to the fixed runner at the upper wall of the arc chamber. The pressure increases slowly after 0.1 ms, indicating a weak pressure wave traveling at the speed of sound (330 m/s).

Streak photographs were made with a fast electronic camera, IMACON, with a streaking time of 700 μ s. Fig. 5 shows a part of the immobility time. At first, there is little expansion of the luminous region between the contacts, then an expansion in the positive X direction (downward) is observed, and finally, the arc starts to move away from the contacts.

Finally, a series of 1600 framing pictures was made with a digitized movie camera featuring a matrix of 10×16 optical fibers. The matrix was scanned within 10 μ s covering an experimental time interval of 16 ms. The complete operation of the CLD from contact opening until current zero has been observed. Fig. 6 contains a sequence of pictures during immobility time with an interval time of 50 μ s.

Fig. 4. Measuring results of the CLD actually used for comparison with the calculated data, showing current I (top), arc chamber pressure p (middle), and arc voltage U (bottom).

Fig. 5. Streak photograph of CLD performance covering the final part of the immobility time and the first part of the arc movement. Exposure time 700 μ s.

V. RESULTS AND DISCUSSION

Fig. 4 also shows the measuring results to which the calculations are related. At $t = 0$, the contacts open, and the voltage between the contacts jumps toward 17 V. This is the well-known electrode voltage drop, necessary to sustain the arc by evaporating and ionizing electrode material. After this, the voltage increases steadily. The current is already at a level of about 2500 A, and continues to increase. The pressure stays at 1 atm, and starts to rise gradually after about 100 μ s. This means that there is no shock wave passing by the pressure probe. The traveling time of 100 μ s is in good agreement with the distance of 30 mm and the sound speed of 330 m/s.

Fig. 7 displays the calculated increase in pressure in space and time for the central region. Here, too, it is obvious that no shock wave is generated during the immobility time, and that the first pressure wave reaches the probe at $x = 0.05$ m just after 100 μ s. Around the arc location, $0.017 < x < 0.022$ m, a high-pressure peak is observed which is caused by the pinch effect of the magnetic field.

Fig. 8 depicts the temperature distribution in space and time for the central region. After an initial expansion of the temperature profiles in both the upstream and downstream directions, it should be noted that after about 160 μ s, the expansion is in the downstream direction only. This transport of hot gas is a result of the Lorentz force $J \times B$ acting upon the hot gas in the arc region in the positive X direction. After 456 μ s, this heat wave has traveled only 20 mm. This performance is in close agreement with the expansion of the luminosity

Fig. 6. Pictures sequence made with a digitized movie camera with 16×10 optical fibers in the XY plane of switching-off performance of the CLD from 0 to $750 \mu\text{s}$, with time step $50 \mu\text{s}$.

Fig. 7. Pressure distribution in the central region as calculated for the schematic CLD depicted in Fig. 1, with time as a parameter. The high peaks show the influence of the magnetic pinch force.

Fig. 8. Central temperature distribution for the CLD of Fig. 1, with time as a parameter.

wave shown in the streak photograph of Fig. 5 and the framing pictures of Fig. 6.

Fig. 8 also clearly shows that, during the first $100 \mu\text{s}$, the air temperature is not high enough to sustain the arc. The vapor jets of electrode material still have to sustain the arc (Raizer [2]). After about $160 \mu\text{s}$, when the air temperature rises above 7000 K , the ambient gas can start to participate in the conduction of the arc. Also, the central velocity increases

strongly (Fig. 9), and the temperature profile expands in the downstream direction thanks to the masses of hot gas that are pumped through the arc region by the Lorentz force. Meanwhile, the negative velocity in the wall regions starts to grow, indicating the creation of a double vortex. We notice from Fig. 10 that the peak value of the current density distribution is moved to the downstream edge of the arc region, $17 < x < 22 \text{ mm}$: the arc tends to move in the downstream direction.

Fig. 9. Development of the central and wall region velocities, calculated at the arc location ($x = 20$ mm).

Fig. 10. Current density distribution, calculated for the CLD of Fig. 1, with time as a parameter.

Fig. 11. Measured and calculated pressure as a function of time at the location of the pressure probe, $x = 0.05$ m.

In Figs. 11 and 12, we see the measured and calculated pressures and arc voltages, respectively. During the time interval from 0 to 500 μ s, a very good agreement between measured and calculated quantities is found. It should be noticed that the calculated arc voltage refers to the arc column only. The model does not include the electrode voltage drops,

Fig. 12. Measured and calculated arc voltage. The initial measured step of 17 V is added to the calculated results because the model does not take the sheath voltage drop into account.

measured as the initial voltage step of 17 V, which has been added to the calculated values. From Figs. 11 and 12, we see that there is a sudden surge in both measured pressure and arc voltage at time moment $t = 500$ μ s: the arc is no longer in the immobility phase, but starts to move in the direction of the arc chamber. Here, the validity of the model ends.

VI. CONCLUSIONS

As was already pointed out in the previous section, the computational results give good agreement with the main physical phenomena found in the experiments. In spite of the uncertainty about the effective open area of the end walls, a striking resemblance was found in the pressure curves.

The computations with the three-layer model give a good account of the electromagnetic quantities which is proved by time development of the arc column voltage.

The expansion of hot gases into the arc chamber, due to the pumping effect of the double vortex, found from the simple three-layer model, was clearly confirmed by the optical measurements. It seems that the arc starts to move when enough highly ionized gas is present in the arc chamber. The endurance of the arc immobility is partly due to the lack of electrically conducting gas in the arc chamber.

It can be concluded that the simple three-layer model gives an account of the main gas-dynamic phenomena during the immobility time of the CLD.

The results obtained with the three-layer model can be used very well as initial conditions for a full 2D-t computation of the arc movement through the arc chamber.

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