Simulation on Arc Movement under Effects of Quenching Chamber Configuration and Magnetic Field for Low-Voltage Circuit Breaker

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1. Introduction

Low-voltage circuit breakers are used to switch on and off the electrical current. Its voltage is up to 1 kV with the current in the range of some kAs. When a fault current occurs in the circuit, the contacts of the breaker are separated with an electric arc established. After a short stagnant time, the arc column moves along the electrodes toward the quenching area under the action of the Lorentz and aerodynamic force. During this course, the gas convection, heat conduction and radiation act on the arc motion together. Because of the complicated processes, many papers [1]–[3] mainly depended on the experimental means to investigate the arc behaviors before. However, with the development of the computer performance and the appearance of many software packages, more and more researchers investigate the electrical arc behaviors by the simulation method. Thus, some of the arc parameters, which are not accessible in experiments, can be obtained from simulation results.

In recent years, many papers contributed to the study of the low-voltage arc simulation. Paper [4] creates an arc model which assumes the arc column to be a chain of small rigid cylindrical current elements without considering the effect of the aerodynamics. A two-dimensional (2-D) model is calculated by the magnetohydrodynamic (MHD) approach in paper [5] and the plasma column is considered as vertical and independent of the vertical coordinate. Paper [6] also contributes to a 2-D axis-symmetric plasma model. In Karetta and Lindmayer’s paper [7], [8], a 3-D chamber enclosed by electrodes and walls is simulated with the heat conduction of electrodes included. However, only a quarter of the chamber is modeled because the authors deal with the electrical potential boundary condition on anode/arc interface in the same way as the cathode/arc interface. Some authors like Schlitz et al. construct several arc simulation models [9], [10]. In their first paper [9], a numerical model is formulated to simulate 2-D and 3-D arc columns with and without the inclusion of the self-induced magnetic field respectively. Their second paper [10] investigates the effects of an external magnetic field and the presence of gassing materials on a 3-D arc column but the arc root is fixed on electrodes. Papers [11], [12] start from a stationary calculated result which is used as the initial state of the transient simulation. The authors determine the position of the arc root by calculating the electrical conductivity of element volumes. The cathode current distribution is only dependent on the coordinate and the heat conduction of electrodes is not considered in this literature.

However, the effects of different external magnetic field and configurations of the arc chamber such as outlet area and splitter plates on the arc movement have not been systematically discussed in published literatures. Mechanisms of some phenomena in the arc plasma during arc movement such as arc column shrinkage, a bulge in front of the arc column and a tail in the rear of the arc column also have not been analyzed in detail.

In this paper, we mainly focus on the simulation of the arc movement influenced by different geometry configurations of the arc chamber and external magnetic field. By different geometry configurations of arc chamber, we mean the simplified chamber is with and without splitter plates and its outlet area is changed. Because the arc behaviors include an electromagnetic process coupled with aerodynamic action, we perform the arc simulation work by the 3-D MHD approach. The governing equations are solved by a modified Computational Fluid Dynamics (CFD) code (Fluent 6.1).

During the simulation, we adopt different electrical potential boundary conditions on two electrode/arc interfaces. The heat conduction from plasma to electrodes is also taken into account. The self-magnetic field is obtained by the potential vector and an external magnetic field is imposed on the calculated domains.

According to the calculated results, several phenomena of the moving arc are fully presented and analyzed. With a ‘bulge’ visible in the front and a tail in the rear, the arc column shows a shrinkage phenomenon near the electrode.
The head of arc column in \( x-z \) plane shows somewhat like part of an ellipse. Additionally, the arc motion influenced by the different geometry configurations of the arc chamber and external magnetic field is discussed in detail. Finally, the arc movement is investigated experimentally to verify our simulated results.

2. Mathematical Formulation

2.1 Hypotheses

To reduce the complexity of the arc physics, a few assumptions as follows are used in this paper [11].

1. The plasma in the chamber is in the state of local thermodynamic equilibrium.
2. The arc ignition and extinction processes are not included in the simulation.
3. Not considering vapors from electrodes and wall material.

2.2 Equations

The finite volume method (FVM) is a general way to describe the fluent governing equations. The conservation laws of the compressible fluent are described by Navier-Stokes and energy equations [13], which include several coupled transport equations written as follows.

1. Mass conservation equation

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0
\]  

2. Momentum conservation equation

\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{V}) = -\nabla q_{rad} + S_i
\]  

with

\[
S_i = \frac{\partial p}{\partial x_i} + \rho \vec{j} \cdot \vec{V} + (\vec{J} \times \vec{B})_i
\]  

3. Energy conservation equation

\[
\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho h \vec{V}) = -\nabla q_{rad} + \left( \frac{\lambda}{c_p} \nabla h \right) + \frac{\partial p}{\partial t} + S_h
\]  

where

\[
S_h = \sigma E^2 - q_{rad} + q_t
\]  

The right part of Eq. (5) includes Joule heat, radiation energy and dissipation heat respectively. In order to simplify the calculation of the radiation energy from the arc column, we assume the plasma to be optically thin [14]. Thus, the radiation energy loss can be defined by

\[
q_{rad} = 4\pi e_n
\]  

where \( e_n \) is the net emission coefficient.

The electrical field is obtained by equations

\[
\nabla \cdot (\sigma \nabla \phi) = 0
\]  

The current density is defined by

\[
\vec{J} = \sigma \vec{E}
\]  

The magnetic field \( \vec{B} \) is obtained through calculating the potential vector as follows [11]

\[
\nabla \times \vec{A} = -\mu \vec{j}
\]  

\[
\vec{B} = \nabla \times \vec{A}
\]

In above equations, \( \rho \) is the density, \( \sigma \) electrical conductivity, \( c_p \) specific heat, \( \eta \) dynamic viscosity, \( \lambda \) thermal conductivity, \( \mu \) air magnetic permeability, \( t \) time, \( p \) pressure, \( \phi \) electrical potential, \( S_i \) momentum source term \( (S_x, S_y, S_z) \), \( u_i \) velocity \( (u_x, u_y, u_z) \), \( S_h \) enthalpy source term, \( h \) enthalpy, \( q_t \) viscous dissipation, \( j_i \) current density \( (j_x, j_y, j_z) \), \( \vec{A} \) magnetic potential vector, \( \vec{B} \) magnetic flux density, \( \vec{E} \) electrical field, \( \vec{V} \) velocity vector and \( \vec{J} \) current density.

The air plasma physical properties \((\sigma, \rho, \lambda, \eta, c_p)\) described above, which depend on the temperature and pressure, are taken from the literature [15].

3. Geometry and Boundary Condition

In order to reduce the complexity of the simulation, two simplified geometries (Fig. 1) are used as arc chambers in this paper. The dimension of each geometry is \( 50 \text{mm} \times 8 \text{mm} \times 8 \text{mm} \) in the \( x-, y-, z- \) direction and the origin of the coordinate is at the center of the chamber. Enclosed by electrodes and sidewalls (not shown in Fig. 1), both the arc chambers shown in Fig. 1(a) and Fig. 1(b) are filled with air. The sidewalls have a thickness of 5 mm. The current I passes through the anode rail (A), cathode rail (C) and the arc plasma. Both the anode and cathode rail have a thickness of 5 mm, width of 8 mm and length of 50 mm. The outlet (O) is used to connect the inner air volume with the atmosphere outside the chamber. The area of the outlet can be adjusted. Figure 1(b) shows two splitter plates (P) at the right end of the geometry. Between the plates and the electrodes are also outlets. Both the sidewalls and plates are made of insulating material.

According to the general way to deal with the velocity in hydromechanical computation, no-slip boundary condition is imposed on all the wall/arc interfaces. The static pressure at all outlets is set to zero and all the outside of the
sidewalls have a temperature equal to 300 K. The heat flux from the plasma to the outer atmosphere through the sidewalls can be defined by one dimension equation [16].

\[ q = -k(T - T_0)/d \]  

(12)

Where \( k \) is the thermal conductivity of the wall material, \( T \) is the temperature of the internal surfaces of sidewalls, \( T_0 = 300 \) K and \( d \) is the thickness of sidewalls. The temperature calculation of the electrodes is also taken into account in our work because of high temperature of the arc volume. At the interfaces of the electrodes and the air plasma, the heat is transferred from the air plasma into the electrodes according to the energy transfer conservation law. Thus, the temperature of the elements in each side of the electrode/arc interface is coupled during the calculation. However, the Joule heating in the electrodes is unconsidered in this paper.

Described by Eqs. (10) and (11), the potential vector is used to calculate self-magnetic field of the arc in this paper. Although potential vector decreases to zero in infinite points, it is not feasible to build the calculated region without limits due to confined memory of computer. According to the fact that the magnetic field decreases with the reciprocal of \( r^2 \) (\( r \) is the distance from the current source), we set the boundary condition of the potential vector to zero at some distance away from the arc chamber.

According to Eqs. (8) and (9), the current density is used to define the electrical potential boundary condition. Due to the current emission contribution of the cathode, a current density also should be imposed on the interface of cathode and arc plasma. However, it is difficult to decide the real distribution of the current density at the cathode/arc interface. In this paper, the Richardson’s law is used to decide the current density at the cathode/arc interface, i.e., we mainly consider the mechanism of current thermo-emission [17],[18] at the cathode. Thus, the current density at this boundary is mainly dependent on the temperature of interface elements and the total arc current. As for the anode/arc interface, we take it as a collector for negative particles. Thus, Dirichlet condition is used to define the potential boundary condition, i.e., zero electrical potential is imposed on the anode/arc interface in this paper.

4. Simulation and Results

For the symmetry of the calculated arc chamber, only half of the geometry is modeled in this paper to save memory and calculation time. Hexahedral cell configuration is used to mesh the calculated domains. According to the maximal velocity and the mesh size in calculation, the time step size is set to 1 \( \mu \)s.

During the simulation, the arc starts in the center position of the chamber and its initial state is from a stationary simulation results without considering the magnetic force. When the simulation begins, an external magnetic field \( B_{ez} \) in the z-direction is imposed on the calculation domains. The calculation current 120 A is applied in this paper.

4.1 Temperature Distribution and Arc Configuration

For the arc chamber of Fig. 1(a), the temperature distribution sequence of the \( x - y \) plane in the middle of the geometry at different time steps is presented in Fig. 2, with \( B_{ez} \) equal to \(-5\) mT and the percentage of the outlet area equal to 20\%. Each frame of the Fig. 2 shows that the maximal temperature (about 20000 K) is in the core of the arc column. At \( t = 0 \) ms, the arc column starts from the center of the chamber (\( x = 0 \) mm) and the magnetic field is applied on the calculation domains. From the time between 0.00 ms and 0.3 ms, the arc is nearly motionless because of low initial velocity. While moving along electrode rails, the arc column’s shape changes much because the velocity is raised more and more. At about \( t=0.86 \) ms, a ‘bulge’ is visible in front of the arc column near the anode. This fact is caused by the effect of magnetic force and gas dynamics. To some extent, such phenomenon is consistent with the results from the literature [3] in which the ‘bulge’ is called ‘nose.’ It presents some figures which show a ‘nose’ exiting in front of the arc column. Such fact proves that the method used in our simulation work of this paper seems reasonable to study the arc movement characteristics. Additionally, it is clear to see that the arc column size is different on the different \( x - z \) plane. It looks ‘wider’ near the plane \( y \approx -2 \) mm and ‘thinner’ near the electrodes. From time between 1.30 ms to 1.911 ms, a tail is visible in the rear of the arc obviously. It can be explained by a gas flow which is contrary to the arc moving direction. Such gas flow is mainly caused by pressure difference between the arc core and the rear of the arc column. Also, we can see the arc core looks somewhat bended from the time between 0.860 ms and 1.917 ms due to the action of the external magnetic force.

Figure 3 partially presents the temperature distribution of the \( x - z \) plane (\( y = -2 \) mm) at \( t = 1.513 \) ms for the same condition as Fig. 2. From the contour, the temperature of the arc core is higher than other parts of the figure. In addition, it is clear to see that there is a long tail in the rear of arc column.
Fig. 3 Temperature distribution of the $x-z$ plane ($y = -2$ mm) at $t = 1.513$ ms for the arc chamber described in Fig. 1(a) under the same condition as Fig. 2.

Fig. 4 Plasma flow field of the arc chamber under the same conditions as Fig. 2 with a maximal velocity 151 m/s.

Fig. 5 2-D vector of the velocity in $x-z$ plane ($y = -2$ mm) corresponding to Fig. 4.

and its temperature reaches to several thousands of K. At the action of the magnetic field force and gas dynamics, the head shape of the arc column looks somewhat like part of the ellipse.

4.2 Arc Configuration Mechanism from the Plasma Flows

Figure 4 and Fig. 5 show the plasma flow field at $t = 0.86$ ms for the same conditions as Fig. 2. Figure 4 presents the velocity vector with the temperature contour ($T > 6000$ K) accompanied. The maximal value of velocity is about 151 m/s. It is clear to see that the arc plasma jets from the cathode and anode meet with each other near the $x-z$ plane ($y \approx -2$ mm), where the direction of the jets is turned forward under the function of the magnetic force. Such flow field can be used to explain the cause of the ‘bulge’ phenomenon presented in Fig. 2. In addition, the plasma jet from the cathode is stronger than the anode, which is caused by different electrical potential boundary conditions defined on the two electrodes. Figure 5 presents 2-D plot of the velocity vector in $x-z$ plane ($y = -2$ mm). Two flow vortices can be observed near the arc core, which is accordant with the result of literature [5]. It can be used to interpret the elliptic shape of the arc head shown in Fig. 3.

4.3 Arc Shrinkage and Current Density Distribution

As the same condition of Fig. 2, a distinct current density contour for two different $x-z$ plane ($y = -2$ mm, $3.5$ mm) at a given time $t = 1.513$ ms is shown in Fig. 4. The plane of Fig. 6(a) is near the ‘bulge’ and Fig. 6(b) is near the electrode. By contrast, the maximum current density value in Fig. 6(a) is lower than Fig. 6(b). On the contrary, the area of current contour in Fig. 6(a) is higher than Fig. 6(b) because of the same current value passed through. Thus, a shrinkage phenomenon, which is also can be seen in Fig. 2, occurs near electrodes with its average current density higher than other areas. Such kind of fact is caused by the effect of self-induced magnetic field and the lower electrodes temperature. Accordingly, the self-induced magnetic field and force are higher in the vicinity of the arc root and this effect contributes to a plasma jet flow in the arc chamber.

4.4 Arc Motion and Phenomena under Different Conditions

The arc position is decided by the average position value $x_a$ of two arc roots in anode and cathode. Figures 7–10 show the arc position curve under different conditions. Figure 7 presents a group of arc position curves calculated under the effect of different $B_{ez}$ ($-2$ mT, $-5$ mT, $-8$ mT and $-10$ mT) for the chamber not including splitter plates with the outlet fully opened. At the original time of the curves, a small shift is visible because the around area of the electrodes near the arc roots is already pre-heated in the initial state of simulation [7]. The curves subsequently rise slowly till $t \approx 0.3$ ms, which means the arc speed is relatively lower in this period. After $t \approx 0.3$ ms, the curves rise faster because the arc column is accelerated rapidly. On the other hand, it is clearly to see that the more $B_{ez}$ is raised, the sooner the arc motion is finished.
For the chamber presented in Fig. 1(b), the simulation work is also carried out to study the effect of splitters plates on the arc motion. Figure 8 shows the arc root position of the calculated results with \( B_{ex} \) equal to \(-3\), \(-5\), \(-8\), \(-10\) mT and the outlet fully opened. The calculation is stopped when the arc column arrives at the position \( (x = 15\,\text{mm}) \) of plates for this model. It is obviously to see that the curves are somewhat different from the results shown in Fig. 7. After a nearly motionless period at the beginning, the arc column is accelerated and each curve rises fast until the arc velocity is decelerated again. Such a slowdown phase of the arc motion is caused by the fact that two splitter plates and the cold gas in front of the arc column block the advance of gas flow. When the cold gas is pushed out of the gaps between the electrodes and plates, the arc moves along rapidly again. It can be observed that the block effect of the plates is more significant when \( B_{ex} \) is decreased. For this model, when \( B_{ex} \) reaches to about 10 mT, the block effect of the plates is nearly unnoticeable.

Figure 9 shows the calculated arc position curves for the chamber without splitter plates under different outlet areas with \( B_{ex} \) equal to \(-8\) mT. It is noticeable that the arc motion during the time interval 0–0.3 ms is independent of outlet areas. After this interval, the outlet affects the further arc motion strongly. The more the outlet is dammed, the more the arc motion is delayed. However, it should be noted that the difference between the curve 5 and 6 is smaller compared with other curves, which means that when the outlet area percentage is raised to some value, its change leads to little influence on the arc motion.

Figure 10 shows arc position curves calculated under different outlet areas for the chamber including splitter plates with \( B_{ex} \) equal to \(-10\) mT. The arc motion during the time interval 0–0.2 ms is independent of outlet areas. After this interval, the outlet influenced the further arc motion strongly.

5. Experimental Results

Under the same condition as Fig. 2 described, the distance versus time diagrams of the calculated and experimental results are presented in Fig. 11 to verify the calculated model. A KODAK EKTAPRO hi-spec motion analyzer is used in experiments to record the arc motion pictures. It can be operated at a maximal speed of 12000 frams/sec. Considering the influence of random disturbance on the arc movement, a group of experiments were carried out on the same condition. It is clearly to see that the arc velocity of each experiment is relatively lower at the beginning of the arc motion and rises rapidly during the rest of the time. Such phenomenon agrees to the calculated results well. From the graph, there is a small difference between the calculated and experimental results. Such difference might be caused by the incomplete calculation of the magnetic field and several hypotheses used in the simulation. The magnetic field caused by the current through electrodes is neglected to reduce the calculation time. Such fact leads to the result that the arc position of the simulated curve is lower than the experimental results after about \( t = 0.3\,\text{ms} \).

Figure 12 shows the arc motion pictures for the chamber described in Fig. 1(b) with the magnetic field equal to
−3 mT. And the corresponding position curve is shown in Fig. 8(curve 1). From the graph, the arc column is delayed by the plates at about 0.583–1.083 ms and such fact partially validates the simulated methods used in this paper.

6. Conclusion

Based on the MHD theory, two simplified chambers with different geometries are used in this paper to calculate the arc motion with a CFD code. From the distribution of the temperature and current density, some phenomena of the moving arc are obtained and discussed in detail. Also, we investigate the arc motion by adapting external magnetic field and different geometry configurations of the arc chamber. Generally, through the analysis of the behavior of the arc motion described in this paper, several conclusions are made as follows.

1. The maximal temperature is in the core of the arc column and the head shape of the arc column during the movement looks somewhat like part of the ellipse.
2. Near the electrodes, the arc column takes on a shrinkage phenomenon due to lower temperature of electrodes and self-induced magnetic force in these areas.
3. During the arc motion, a ‘bulge’ occurs in front of the arc column and a tail is visible in the rear of the arc column with its temperature up to several thousands of K, which is caused by the plasma flow field in the chamber.
4. The external magnetic field and outlet area act on the arc motion strongly. Also, the splitter plates block the arc movement and a slowdown phase can be observed from the arc position curve. However, such block effect of the plates can be weakened by raising the external magnetic field.

Acknowledgments

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References


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