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Cite as: AIP Advances 7, 125006 (2017); https://doi.org/10.1063/1.5001738
Submitted: 26 August 2017. Accepted: 23 November 2017. Published Online: 07 December 2017

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Modeling and numerical simulation of anode activity and arc motion in a transverse magnetic field

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(Received 26 August 2017; accepted 23 November 2017; published online 7 December 2017)

Vacuum interrupters based on transverse magnetic field contacts now are widely used in medium voltage circuit breakers. The arc motion under the transverse magnetic field (TMF) plays a decisive role in the interruption. In this paper, we focus on the movement of vacuum arc driven by TMF and anode thermal process during the arcing. Then, based on the principle of conservation, a transient two-dimensional anode activity model (subjected to TMF constricted arc) is established. The state change of material, evaporation from contacts and motion of molten pool are also considered in our model. By considering the arc motion in the anode activity model, the transient anode thermal process and the movement of constrict arc under TMF are studied, respectively. The simulation predicted that average speed of arc is not higher than 200 m/s. In the simulation, the anode surface is completely melted near the current peak with 200 μm molten layer. In addition, the influence of movement of molten pool on the arc speed is analyzed, finding that the movement of the bath accelerates arc speed, but weakens the surface melting at the same time. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5001738

I. INTRODUCTION

The vacuum circuit breaker is a kind of switch equipment which is widely used in the medium-voltage field in the power system. The forms of vacuum arc have great influence on the breaking property of the vacuum interrupters. For current above 15 kA, arc becomes constricted. The interrupting ability of vacuum interrupters without arc control methods is limited by the constricted arc. For better breaking ability, two arc control methods are used, respectively transverse magnetic field (TMF) and axial magnetic field (AMF). The AMF contacts keep arc in diffuse mode at high current due to the action of magneto-dynamic effects. The TMF, generated by spiral-type or cup-type contact, moves the constricted arc over the contact surface. The movement of the arc makes the energy of the contact surface to be redistributed, avoiding excessive heating of the contact and reducing the ablation of a fixed area.

The motion characteristics of TMF constricted arc directly relates to the energy distribution input into the electrodes. Some researchers have done preliminary studies on the movement of TMF arc. Considering the energy conservation between the arc column and the contact surface, Dullin established a one-dimensional arc motion model to calculate the upper limit of the velocity of the arc. The finite difference method and the Stefan equation were used to calculate the heat transfer of the contact surface. For more accurate results, Teichman et al calculated the amount of evaporation from contacts based on mass conservation and momentum conservation principles. Momentum conservation was also considered in Dullin et al’s subsequent models. Subsequently, Branston et al used a new calculation method of evaporation in their model. In the perspective of a more in-depth study of the physical process of arc motion driven by TMF, Delachaux et al established a
preliminary two-dimensional arc motion model based on the magnetohydrodynamic (MHD) approach and made an initial study of the arc motion over slits, finding that gap distance had a great impact on the movement of arc.\textsuperscript{2,12–14}

When the arc is constricted, the anode will be in active state, melting and even evaporating. The metal vapor is ionized by colliding with the plasma. It makes anode become a source of the plasma. The anode active is a great challenge to interrupters. Watanabe \textit{et al} established a one-dimensional mathematical model of the anodic thermal process to calculate the anode temperature and molten depth at zero time.\textsuperscript{15} Gellert and Egli took into account the phase transition of the anode material and established another one-dimensional model where the influence of energy flow on the anode temperature and the molten depth was studied.\textsuperscript{7} The relationship between melting depth and arc current was studied by Schellekens and Schulman based on a one-dimensional model.\textsuperscript{16} Subsequently, Beilis \textit{et al}\textsuperscript{17} and Wang \textit{et al}\textsuperscript{18} established two-dimensional transient models, respectively. The anode thermal process was obtained by simulations.

During arcing, the molten pool is likely to move under the action of electromagnetic force, arc force, viscous force, Marangoni stress and etc. Some experimental studies have been made on this phenomenon. A significant melting of the anode and the movement of the molten metal were observed in Refs. 19 and 20. Schellekens and Schulman observed the flow of molten metal on the anode surface along the radial direction during the study of AMF arc.\textsuperscript{16} They believed that the movement of the molten metal redistributed the energy injected into the anode. Yang \textit{et al}\textsuperscript{21,22} and Jia \textit{et al}\textsuperscript{23,24} made a study on the cup-shaped AMF contacts, finding that the anode pool rotated during arcing and the plasma jet from cathode and the direction of the magnetic field had a significant effect on the rotation. In the simulation, Wang \textit{et al} established a model of anode molten pool under AMF.\textsuperscript{25,26}

At present, most of the research on the motion of the arc driven by TMF is based on the one-dimensional motion model. The arc size and the current density used in those are given referring to experimental data. However, some data in these models are still empirical values. In addition, the physical parameters of the contact material used are still constants. The existing two-dimensional models are really limited. The process of arc motion during the alternating current is not considered and the reciprocating motion of the arc on the surface of the contact is not studied in depth. In addition, studies of anode thermal process and the motion of molten pool are mainly focused on AMF contact. There is no sufficient research on the studies of TMF contacts, neither the anode thermal process nor the relationship between arc motion and anode activity. In order to further understand the behavior of the arc in the transverse magnetic contact, it is necessary to study the arc motion and anode ablation during the whole arcing and analyze the interaction between the anode ablation and the arc motion.

In this paper, the arc motion in the transverse magnetic contact and the thermal process of the anode surface during the arcing are studied. A transient anode activity model is established and the arc motion is considered in the model. The arc behavior and anode thermal variation process are calculated. The phase transition, latent heat of melting and evaporation are taken into account in our model, and the change of the physical parameters with temperature is also considered. Simulation calculations are implemented via fluent software. And the combination of the arc motion with the anode thermal model is achieved by user-defined function (UDF).

This paper includes primarily two parts. In the first part, arc motion is considered in anode activity model (the vapor flux and surface temperature calculated from the anode activity model provide a criterion for arc motion, while the movement of arc provides a new condition for the simulation of anode activity at the next moment). The arc speed, anode surface temperature distribution and anode vapor flux can be obtained. In the second part, considering the action of surface tension and arc force, influence of the movement of the molten pool on the arc motion and on the ablation of the anode is analyzed.

II. PHYSICAL MODEL

Contacts in the vacuum circuit breaker mainly contain electrode cup, contact plate and conduct stem. As the arcing time is short, the heat passed away by the electrode cup and conduct stem could be neglected. So, in this model, only the contact plate is modeled.
When the arc current attains certain value, the anode becomes active. The energy taken away by evaporation cools the anode. The anode achieves energy balance under the continuous action of heat flux density injected into anode, energy dissipated by heat conduction and energy loss through evaporation.

Considering the complexity of calculation, a two-dimensional model referring to the actual cup-shaped contact (radius is 30mm, thickness of contact plate is 2mm) was built as a first step, showed in FIG. 1. In this model, the usual circular contact is simulated as a straight rail. The reciprocating motion of arc is simulated by continuously "removing" the arc back to the left side when it arrives at the right side. Energy transfer between the two sides is also considered through UDF. The length of this rail is equivalent to the circumference of a contact. The simulated anode is chosen to be pure copper. Then, a two-dimensional time-varying model is established.

This model is based on the following assumptions:
1) The energy dissipated by radiation could be neglected;
2) Convection and turbulence are not considered in the molten pool;
3) The mass loss caused by the ejection of liquid droplets is ignored here;
4) Regardless of the anode surface deformation caused by the flow of molten pool and evaporation of anode material;
5) The latent heat of melting and evaporation during phase change are considered;
6) The TMF applied by an external source is distributed homogeneously between two electrodes.

III. MATHEMATICAL MODEL

A. Movement of contracted arc

In the model of Ref. 2, it was proposed that the attachment zones of contacts and arc determine the speed of arc motion. And its results showed that the cathode motion followed well with the anode motion. Moreover, as already found by Hass and Hartman, for constricted high current vacuum arcs, the behavior of arc roots is similar on anode and cathode. Thus, it is reasonable to assume that the phenomena occurring at the cathode is similar to anode and the movement on cathode follows well with the anode arc motion. Then, the movement of anode arc root could represent the whole arc motion.

According to Ref. 8, approximately 40% of the total energy of arc transmitted to each electrode. Some of these energy heats the anode temperature through heat conduction, while the rest dissipates through evaporation. The temperature distribution of electrodes determines the behavior of arc. According to Refs. 5, 9, and 10, we assume that the arc root can only move as fast as there is time to heat the contact surface up to boiling temperature. Thus, we claim that the arc will only move when the temperature near the arc root exceeds a certain threshold. The velocity of the arc can be calculated through the position of the arc root. From Ref. 13, calculations showed that in case of a copper electrode, movement of arc on the cathode is possible when surface temperature exceeds 3400K. This condition ensures that the cathode deliver enough flux and thermionic electrons to sustain the arc. And for anode electrode, there also needs to be a high enough temperature to provide enough plasma density in order to avoid a positive anode voltage drop. It is fulfilled when the threshold temperature is chosen to be 2900K, just above the boiling temperature. It provides the high rate of evaporation necessary to enable the anode connection. Thus, here, it
is reasonable to choose the threshold temperature slightly higher than the boiling temperature (for copper, 2868K). This assumption ensures there is sufficient vapor in the direction of arc movement. There is no direct experimental proof for this assumption. However, a previous study has evaluated that for a TMF constricted arc, the temperature of the foot point at the anode was between 3300K and 3600K, while for the cathode was between 3200K and 3400K, which supports our assumption.

B. Mathematical model of anode

Generally, there are two methods to solve the melt/solidification problem: method of solving temperature and method based on enthalpy-porosity technique. The method based on the enthalpy-porosity technique is adopted here, which has a higher accuracy. In this method, enthalpy is solved variable and the melting zone is treated as a porous zone and the enthalpy-porosity formulation is used to solve the heat transfer. Detailed introduction is presented in Ref. 18.

Whether the metal density changes with phase transition makes a great difference on the shape of molten pool, as show in FIG. 2. If the density of the metal did not change with the phase transition, the ideal shape would look like FIG. 2(a). If the reduction of the metal density was considered when the phase changed from solid to liquid, the surface of the molten pool would be bulged, as picture in FIG. 2(b). But in practice, the surface of molten pool is concave under the effect of arc pressure, while bulged under the action of surface tension. The actual shape is showed in FIG. 2(c). After the molten pool is formed, it flows under the influence of internal forces and external forces. The forces acting on the molten pool can be divided into body force and surface force, the motion is shown as in FIG. 3. The body force is applied to the inside of the molten pool, including electromagnetism and buoyancy. The surface force is applied to the surface of the molten pool, including the shear stress and the normal stress caused by the surface tension gradient and surface curvature, and the arc

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**FIG. 2.** Shape of molten pool; (a) ideal shape; (b) shape considering density change of material and (c) actual shape.

**FIG. 3.** Force analysis diagram of molten pool.
pressure from plasma. The effect of normal stress could be ignored when the deformation of anode is small. The electromagnetic force and buoyancy make liquid metal convect in molten pool, while the Marangoni force and arc force are the main drivers pushing the pool moving to surroundings. Here, we mainly discuss the influence of molten pool moving around on the arc motion and the electromagnetic force and buoyancy are neglected.

1. Control equations

In the fluent software, the enthalpy of material contains the sensible enthalpy and the latent heat.

\[ H = h_{\text{ref}} + \int_{T_{\text{ref}}}^{T} c_p dT + \Delta H \]  

(1)

The first two terms of the right side are the sensible enthalpy, where \( h_{\text{ref}} \) is the reference temperature, \( T_{\text{ref}} \) is the reference enthalpy and \( c_p \) is the specific heat at a constant pressure.

For solidification/melting problems in the FLUENT software, the melting zone is treated as a porous zone in which the latent heat content \( \Delta H \) could be expressed in terms of the liquid fraction \( \beta \) and the latent heat of material \( L \).

\[ \Delta H = \beta L \]  

(2)

The liquid fraction \( \beta \) is closely related to the temperature. When the temperature is not larger than the solidus temperature \( T_{\text{solidus}} \), \( \beta \) is 0; when the temperature is not less than the liquidus temperature \( T_{\text{liquidus}} \), \( \beta \) is 1; when the temperature is between \( T_{\text{solidus}} \) and \( T_{\text{liquidus}} \),

\[ \beta = \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} \]  

(3)

In our model, the energy equation is written as

\[ \frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\rho v H) = \nabla \cdot (\lambda \nabla T) + S_e \]  

(4)

Where \( \rho \) is the density, \( v \) is the fluid velocity, \( \lambda \) is thermal conductivity and \( S_e \) is the source term.

To simplify the calculation, the thermal convection is neglected in the calculation. Moreover, the heat flux transferred into the surface is added in the form of boundary conditions.

If a molten pool is formed, the calculation area will contain solidoid, liquidoid and the mushy zone at the same time. There is no need to solve the momentum equation in the solid region. But momentum source items needs to be added in the phase change process, which forms as:

\[ S = \frac{(1 - f_L)^2}{(f_L^3 + \varepsilon)} A_{\text{mush}} \tilde{u} \]  

(5)

Where \( \varepsilon \) is a very small number, in case of a zero denominator. \( A_{\text{mush}} \) is a constant relating to the mushy zone.

2. Boundary conditions

The boundary condition, as an important input, has a significant effect on the simulation results.

a. Thermal boundary conditions. The thickness of contact plate in our model is 2mm. Considering the melting depth of the electrode is about 200 \( \mu \)m,\textsuperscript{29,30} the heat conduct near the anode bottom is so weak that would be ignored. Meanwhile, the heat conduction from the electrode cup and the conduct stem is not considered. Accordingly, the bottom of anode could be considered to be adiabatic.

\[ \frac{\partial T}{\partial y} = 0 \]  

(6)

Heat transfer between the two boundaries are,

\[ q_{\text{left}} = -\lambda \frac{\partial T}{\partial x} \]  

(7)

\[ q_{\text{right}} = -q_{\text{left}} \]  

(8)
Where $q_{\text{left}}$ is the heat flux transferred into the left side and $q_{\text{right}}$ is the heat flux transferred into the right side.

The heat flux density from arc column is the main condition to solve the energy equation. However, it is difficult to obtain from experiment. In Refs. 2,13 and 14, it showed that an intense heat flux reached the anode surface with a peak value up to several $10^{10}$ W/m$^2$ with current of 30kA and 50kA. And a small peak appeared ahead of anode attachment under the force of TMF, which was different with vacuum arc under AMF, as assumed to be sinusoidal in Ref. 18. Our simulation is based on following conditions: current $I=50$kA, gap distance $d=7.5$mm, the applied TMF is homogeneously distributed and corresponds to 44mT/kA. Then, a reasonable distribution of heat flux density is given, as shown in FIG. 4. Considering that the heat flux density to the anode is closely related to the arc current, a sinusoidal variation of heat flux with time is used here.\(^{(18)}\)

b. **Boundary condition of fluid flow.** At the side and bottom of the anode, the velocity is zero. On the anode surface, the molten pool is affected by the Marangoni force and pressure from arc plasma. The Marangoni force adding through the boundary conditions is shown below.

\[
\eta_1 \frac{\partial u_x}{\partial x} = -d \gamma \frac{\partial T}{\partial x} \tag{9a}
\]

\[
\eta_1 \frac{\partial u_y}{\partial y} = -d \gamma \frac{\partial T}{\partial y} \tag{9b}
\]

Where $\gamma$ is the surface tension.

For arc pressure, its value can reach several tens of bars near the anode, which is close to the saturation pressure corresponding to the surface temperature.\(^{(2,14)}\) Here, the effect of vacuum arc pressure is introduced by adding the source term in Eq. (10), according to the saturation pressure. The saturated vapor pressure $P_s$ can be calculated through Clausius-Clapeyron equation, as shown in Eq. (11).

\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \left( \vec{F} \right) + \rho \vec{g} + \vec{F} \tag{10}
\]

\[
P_s = P_{\text{atm}} \exp \left[ -\frac{\Delta_{\text{vap}}H}{R} \left( \frac{1}{T_s} - \frac{1}{T_{\text{boil}}} \right) \right] \tag{11}
\]

Where $P_{\text{atm}}$ is the atmospheric pressure, $T_s$ is the surface temperature, $T_{\text{boil}} = 2868$ K is the boiling temperature of cooper, and $\Delta_{\text{vap}}H = 300.4$ kJ/mol is the latent heat of vaporization.
IV. RESULTS AND ANALYSIS

The main purpose of our work is to establish the movement model of the vacuum arc driven by TMF and to analyze the thermal motion of anode. In addition, the interaction between anode activity and arc movement is studied. In part A, the movement of constrict arc and the thermal process (including the melting and evaporation) of the anode during the arcing period are analyzed without considering the molten pool moving around. Then, the impact of anode molten pool motion on the arc speed and on the anode ablation is studied preliminarily in part B.

A. Results without considering the molten pool moving around

Arc speed is affected by the temperature near the arc root, and it affects the temperature of the anode surface, in turn. Results in FIG. 5 show that the larger the arc current is, the higher the arc velocity and the temperature of the arc root are. The temperature at the arc root reaches the peak at about 5ms. Moreover, when the arc returns back to the starting point, the temperature (arc speed) at the arc root suddenly decreases and then rises (suddenly rising and then falling). The main reason may be that the heating of the starting point is deeper relative to the other positions on the surface, making the speed become larger suddenly and the temperature decrease correspondingly when returning to the initial position again. As arc moves forward, the arc speed decreases and the temperature of that point rebounds. The line 2 represents the arc speed of each turn. Before 5ms, it increases with the number of turns. On the one hand, it is because that the instantaneous velocity of the arc increases as the current increases. On the other hand, the surface temperature is higher than the initial moment when the arc returns back to the same position, which accelerates the speed of arc correspondingly. The maximum velocity occurs between 6ms and 8ms, which may be affected by the thermal inertia. And the average arc velocity during the arc process is approximately 150m/s.

The anode begins to melt when the current is relatively large. Contours of surface temperature and the melting depth at different moment are described in FIG. 6(a) (Multimedia view) and FIG. 6(b) (Multimedia view). In FIG. 6(a) (Multimedia view), the arc motion can be reflected from the position of arc root (highlighted by a red arrow in figures). Instead of arcing at a fixed area, the movement of arc transfers the energy from arc column to the entire contact, reducing the possibility of breaking failure due to severe local ablation. The reciprocating motion of arc affects the thermal change of anode. In the first turn, the temperature of the lower part of anode has hardly changed. More details can be seen in FIG. 7, a magnified image of temperature change. It dedicats that temperature raises when the arc passes by. Such as the point at 0.05m, since the arc has not moved to this point before 2ms, its temperature is low, about 300K. At 2.5ms, the arc firstly crosses this point and the temperature rises.

FIG. 5. Development of temperature of arc root (1); average speed of each cycle (2); average speed of the whole arc time (3).
to about 2000K. As arc moves forward, energy injected into that point is gradually smaller and its
temperature decreases. Moreover, with the increase in heat flux density, the peak value of temperature
exceeds the melting point and there is an obvious inflection point in the curve. The phase change
occurs near the inflection point. FIG. 7 also indicates that in the first lap the peak temperature of anode
surface increases slightly with time. Comparing the temperature distribution of 2.5ms and 4ms, it can
be found that when the arc returned back the same point at the second lap, the temperature increases
significantly, due to the heating during the first lap.

The contours of liquid fraction at different moment are shown in FIG. 6(b) (Multimedia view).
The copper is in a liquid state when \( \beta \) equals to 1. Form FIG. 6(b) (Multimedia view), it can be seen
that the melting depth increases due to the energy input. The anode is completely melted after the
current peak, with a molten layer about 200 \( \mu m \).

Next, we are interested in studying the influence of a multiturn arc on the thermal behavior of
anode. The variation process of a fixed point (A) is analyzed. The development of surface temperature
and molten depth at point A during the arcing period is depicted in FIG. 8. The results dedicate that
the temperature of point A reaches its first peak, above the critical temperature, when arc firstly
moves to this point, accompanying with a significant melting phenomenon. As arc continues to move
forward, its temperature begins to decrease and the molten metal at this point starts to cool. When
the arc returned back to this point for the second time, the temperature has not yet fallen to the initial
temperature, so the temperature at this moment is higher than the previous cycle and there is a deeper
degree of melting. Before arc current reaches its peak, the energy put into anode is small and the
temperature at this point would drop below the melting point within one round. In addition, there
is a period of stagnation at the temperature near the melting point for the phase transition between
solid and liquid. As the current increases, the temperature rises and the speed of the arc becomes
larger, as a consequence, the temperature would not drop below the melting point within one round.
Correspondingly, the maximum temperature at this point becomes higher and higher and the degree
of melting gets deeper and deeper. After the current peak, the current decreases gradually, but its
temperature is still higher than the melting point, making the point still being in the molten state.
This result indicates that, until the end of the arcing, some part of anode has not yet cooled to solid.
The molten depth evolution in FIG. 6(b) (Multimedia view) describes that the anode are liquid at the
first 200 \( \mu m \) under the anode surface, which means that the constrict arc does cause serious erosion
on the anode. This is important to determine whether the arc can be successfully interrupted at zero
time.
B. Influence of the movement of molten pool

Molten metal moves under the action of pressure of arc plasma, the electromagnetic force, surface tension, buoyancy and other forces. Arc force and Marangoni force are the main force moving bath around. In Refs. 2 and 14, it has been mentioned that the arc pressure nearby the electrodes is about several tens of bars, which is close to the saturation pressure. Therefore, the pressure has very probably a major impact on the molten pool motion. And Marangoni force, which is caused by the change of the surface tension coefficient with temperature, makes the fluid always flows from the lower surface tension to where the surface tension is high. For a positive surface tension coefficient, the higher the temperature is, the greater the surface tension is. While for a negative surface tension coefficient, the higher the temperature is, the smaller the surface tension coefficient is. Here, the surface tension coefficient of liquid copper is negative. So, the molten pool flows from the high temperature to the
FIG. 8. Development of surface temperature (1) and molten depth (2) at a given point (A) on the anode of a TMF rotating arc; (3) represents the melting point.

low temperature by the role of Marangoni force. The flow of the molten bath changes the energy distribution of the anode surface which would affect the movement of the arc. In this part, we focus on the effect of arc force and Marangoni shear stress on the arc motion. Considering the complexity of calculation, the two-dimensional movement model combined with transient two-dimension anode activity model is calculated with a constant current (DC), the influence of molten pool on the arc motion and anode ablation is analyzed.

FIG. 9 (Multimedia view) (FIG. 9(a) (Multimedia view), FIG. 9(b) (Multimedia view)) describes the distributions of anode surface temperature at different moment, showing that the movement of the molten pool changes the distribution of temperature and arc velocity. In FIG. 10, it is obvious that the movement of the molten pool does accelerate the arc speed. In the case of considering the surface shear stress and arc pressure, the temperature at the arc root increases but its melting depth is smaller. One of the reasons is the increase in arc speed. Another may be that the movement of the molten pool makes the energy of the contact surface redistributed, leading to the anode surface temperature distribution being more uniform.

FIG. 9. Anode temperature contours at different moment. (a):considering movement of molten pool, (b):no considering movement of molten pool. The number in bracket represent the rotating revolutions of arc. The arc root is indicated by the red arrow. Multimedia views: https://doi.org/10.1063/1.5001738.3; https://doi.org/10.1063/1.5001738.4
V. DISCUSSION

A. Comparison with simulation results of other researchers

Many researchers have studied the movement of arc driven by TMF based on one-dimensional model. In this part, the existing one-dimensional movement model is improved. The arc speed calculated by this improved method is treated as the input of the anode activity model for the analysis of anode thermal process during arcing time. This is compared with the results in our model.

The arc exhibits in a stable diffuse state if the arc current is not large. When the current increases to a certain value, it begins to constrict and moves along the arcing ring driven by the electromagnetic force. In most cases, the velocity of arc is limited to several hundred meters per second. On the basis of exiting arc motion model, the relationship of arc root area with current (according to Ref. 28) is considered and a new evaporation model is developed (Eq. (11)). The speed of arc under different situations is calculated, as shown in FIG. 11. It can be seen that the arc current and the gap between electrodes have a certain impact on the arc movement. And the larger the magnetic field is, the greater the drive force is, and the faster arc moves.

Arc speed calculated from this model is treated as the input of anode activity model described above. Results are shown in FIG. 12–14.

![FIG. 11. Calculation of arc speed. (1) solution with L=8mm, br=5mT/kA; (2) solution with L=7.5mm, br=44mT/kA; (3) solution with L=10mm, br=44mT/kA.](image-url)
The development of arc speed, temperature variation at arc root and point A are described in FIG. 12 and FIG. 13. In FIG. 12, the arc root hovers a short time at the boiling point at the initial stage, for a production of enough metal vapor to maintain the stable movement of the arc. Compare FIG. 5 with FIG. 12, the tendency of arc speed in our simulation is similar to the results using other researcher’s speed calculation. FIG. 14(a) (Multimedia view) and FIG. 14(b) (Multimedia view) depict the contours of anode surface temperature and liquid fraction at different moment. In comparing FIG. 6(b) (Multimedia view) and FIG. 14(b) (Multimedia view) it can be found that the anode is completely melted with a 200 µm molten layer.

Based on the similar assumption (improved arc speed model assumes that there must be sufficient vapor produced from the electrodes to hold the arc motion; we suppose that only if the temperature near the arc root reaches the threshold value, could the arc move forward, which also ensures enough vapor.), and following the conservation of energy, the conservation of momentum and the conservation of mass, their conclusions are consistent in analyzing the interaction between the arc motion and the thermal process of the anode. But there are also some differences. Actually, due to the Lorentz force, the arc would changes from a straight column into a bowed column. The actual temperature near the arc root is also different from a straight column. The influence of a bowed column and the heat conduction are not considered in the movement models. In addition, some parameters, such as arc...
B. Comparison with other researchers

To verify the correctness of our work, comparisons are made with other studies. The arc speed, varying from 100 m/s to 400 m/s in our models, verifies well with the experimental results in Refs. 8, 31, and 32, which discovered that arc speed was typically some tens of m/s to 150 m/s, but also had velocities of 300-400 m/s. Previous studies have shown that the velocity of the arc in the transverse magnetic contact was about 100-400 m/s. Contact system with an outside diameter of 65 mm was investigated at an arc current of 30 kA in Ref. 29, emerging there were nine turns during arcing. Delachaux et al. has discovered that arc speed varied with the electrode separation and arc current from dozens to hundreds. All of these studies confirms the correctness of our results. For melting depth, results in our simulation showed that the contact surface was completely melted during the arcing, with a melting layer of about 200 µm. This is consistent with the research of Gentsch: they studied the melting and ablation of different structural electrodes. The thickness of the melting layer on the electrode surface was about 150 µm by scanning electron microscopy, and the surface of the contact was completely melted. In addition, the influence of molten pool movement on arc and anode ablation is studied. It is found that the movement of molten pool changes the anode surface temperature distribution and accelerates the arc speed, which is coincide to the finding of Schellekens and Schulman, who studied the thermal effect of AMF contacts and observed that molten metal on the anode surface flowed outward along the radial direction. Through experiment, they believed that the flow of the liquid metal caused the very inhomogeneous energy injected from the arc column into the anode to be redistributed. By qualitative analysis for the interaction between the arc motion and the anode thermal evolution, results of our present simulation have a good agreement with existing researches.

C. Reasonability of heat flux density

For anode, energy balance mainly contains heat flux density injected into anode, energy dissipated by heat conduction and energy taken away by evaporation. Heat flux density given in our work is based on the research of Delachaux et al. Simulation results in Ref. 12 dedicated that the gap distance between the electrodes has a great impact on the behavior of plasma and the arc motion.
For short gap, arc behaves rather like a straight column, whereas for large gap the column is in the form of a bent arc that extends on several millimeters from the arc root in the direction of motion. The may be explained by a greater Lorentz force acted on arc in case of larger gap distance. Thus, it is reasonable that heat flux density for a 7.5 mm gap given here has two peaks. It is also predicted that the peak value of energy flux to the electrodes at a current of 50 kA is up to several $10^{10}$ W/m$^2$.

VI. CONCLUSION

It can be seen from above analysis that there is an apparent melting of the anode during arcing. The arc behavior has a great influence on anode thermal process, and the anode temperature distribution in turn affects arc behavior. In addition, the movement of molten pool may accelerate arc motion. According to the simulation results, we can get the following conclusions:

1. The arc reciprocates on the surface of the contact applied TMF. The alternate motion of arc brings variation to temperature distribution of anode surface. Temperature near the arc root plays a crucial role on the arc motion. Only if a high enough temperature is reached, arc root could move ahead. Besides, arc speed is also related to some parameters, such as arc current, the gap distance between the electrodes and the magnetic field. For large gap distance, the arc is actually bowed. In case of our simulation, arc speed is about several hundred m/s and the maximum velocity occurs between 6ms and 8ms. Temperature of arc root is above 4000K during arc motion.

2. The reciprocating motion of the arc makes cyclic variations in the anode surface temperature. When arc moves to point A at the first time, its temperature reaches the first peak, with obvious melting. Once arc moves forward, the temperature starts to decrease. A second increase in temperature happens when arc returns back to the point A again, accompanied by deeper melting depth. Then, the temperature at that point displays cyclic variations with the reciprocating motion of arc and the melting depth increases gradually.

3. In the high-current transverse magnetic field vacuum interrupters, there is a significant anode melting during arcing. As learnt from the results of our simulation, the fuse zone becomes bigger with the increasing of current, and the whole anode surface is melted near the peak of current. Until the end of arcing, there is still a melting layer about 200 µm.

4. The molten pool moves under the effect of arc force, electromagnetic force, viscous force and the Marangoni stress. The influence of molten pool moving around is analysed in this paper, which is mainly driven by pressure from arc plasma and Marangoni force. The simulation results show that the movement of the molten pool accelerates the arc motion and makes the temperature distribution of the anode surface be even more uniform, thereby reducing the degree of anode ablation.

In fact, the distribution of surface temperature, the evaporation density between electrodes and the structure of the contacts greatly affect the performance of the vacuum circuit breaker. For further analysis, an optimization procedure under 3D model will be established in our next work. And the influence of different heat flux density, different material contact and slots will be considered. Later on, the deformation of the anode surface under the action of arc pressure and surface stress will be simulated, which may provide the basis for the prediction of arc interruption.

ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China (Project No: 51777153).

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