Numerical Simulation and Analysis of Arc Anode Erosion Process with Electrode Rotation

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Abstract. A three-dimensional geometric model of anode contact of vacuum circuit breaker is established. Considering the influence of electrode rotation on vacuum arc and anode thermal process, a physical model of phase transformation process is established for the melting and evaporation of anode surface. The solid-liquid mixing area is treated by the description method of porous media, and the numerical simulation of anode thermal process is carried out. The conclusion is that with the increase of time, the anode surface temperature increases, molten pool development, molten pool depth deepening, in addition, with the increase of electrode speed, the highest temperature on the surface of the contact and the size of the molten pool were reduced, the temperature distribution more uniform. It provides theoretical basis for evaluating the breaking capacity of vacuum circuit breaker.

1. Introduction
The essence of vacuum arc is vapor arc existing in vacuum medium[1]. At present, it has been widely used in many fields, such as vacuum interrupter, vacuum coating, phase controlled vacuum switch and so on.

When the vacuum circuit breaker is rotating, the arc plasma will follow the electrode movement, resulting in the energy flow density of the arc acting on different positions of the anode contact surface, which will have different effects on the thermal process of the anode. Multiphysics established a transient three-dimensional anode model to analyze the phase transformation process of anode after arc, and calculate the temperature change and bath depth change of anode contact surface. The simulation results show the deformation process and temperature distribution of anode during arc combustion[2].

2. Simulation Model

2.1. Physical model
The physical model of anode thermal process under the action of vacuum arc is shown in Fig. 1. The contact of vacuum circuit breaker mainly consists of contact piece, conductive cup and conducting rod.
However, due to the rapid breaking process of vacuum arc, generally within a few milliseconds, the heat loss of conductive cup and conducting rod can be approximately ignored during this period, so the modeling can only be conducted for contact piece.

Because the thermal process of anode develops gradually with time, a transient model should be established. The simulation time is 10ms of one half wave time of power frequency sinusoidal current, and the influence of energy flow density of arc arriving at anode in 10ms arcing time on anode thermal process should be considered. The simulated contact material is set as pure copper, the contact radius is 25 mm, and the contact sheet thickness is 4 mm. The physical model is shown in Figure 2.

In order to simplify the analysis process, the model will be based on the following assumptions: 1) the mass loss due to the evaporation of the whole anode is ignored. 2) The influence of metal vapor injected from anode into vacuum gap is ignored. 3) The deformation of anode contact due to phase transformation is ignored. 4) The heat exchange and radiation of anode in vacuum environment are ignored, that is, only the heat loss of contact surface due to a large amount of metal vapor jet is considered. 5) The effect of melting latent heat should be considered.

2.2. Mathematical model
The phase transformation process of materials still follows three basic equations of fluid dynamics: mass conservation equation, momentum conservation equation and energy conservation equation.

1. Conservation equation of mass
Since the mass loss of anode caused by splashing droplets and evaporating metal vapor during melting is ignored, the equation of mass conservation is expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0$$

(1)

Where $\rho$ is the mass density of copper and $\vec{U}$ is the velocity vector. According to hypothesis (2), this item can be ignored.

2. Momentum conservation equation
Due to neglecting the influence of buoyancy, gravity, electromagnetic force and tension, the momentum conservation equation is expressed as follows:

$$\frac{\partial (\rho \vec{U})}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U}) = -\nabla \cdot (\mu \nabla \vec{U}) - \nabla p$$

(2)

Where $p$ is the pressure term and $\mu$ is the viscosity coefficient.

3. Energy conservation equation
In the process of arc combustion, the energy exchange between anode and surrounding environment mainly includes: the input of electron and ion energy flow from anode surface, heat conduction inside anode contact material, thermal radiation from anode surface to surrounding medium, and energy loss due to external injection of metal vapor. The energy conservation equation per unit volume of anode contact material in terms of enthalpy is expressed as follows:

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho H \vec{U}) = \nabla \cdot (k \nabla T) + S$$

(3)
Where $H$ is the enthalpy of the electrode, $K$ is the thermal conductivity of the contact material, $T$ is the temperature, and $S$ is the heat source term.

The enthalpy $H$ of electrode material consists of two parts:

$$H = h + \beta L$$  \hspace{1cm} (4)

Where $H$ is the apparent enthalpy, $\beta$ is the liquid phase ratio, and $L$ is the latent heat of the material.

Because there is a mixing region between solid phase and liquid phase in the material, this part of mixing area is usually assumed to be porous medium, and the transformation process of solid and liquid phase is reflected by the flow of porous medium. $\beta$ represents the fluid fraction at melting and the proportion of solid-liquid components in reaction fluid is expressed as follows:

$$\begin{align*}
\beta &= 0 \quad T < T_s \\
\beta &= \frac{T - T_s}{T_l - T_s} \quad T_s < T < T_l \\
\beta &= 1 \quad T_l < T
\end{align*}$$  \hspace{1cm} (5)

Where $T_s$ is the solid phase temperature of the material and $T_l$ is the liquid phase temperature of the material. The isothermal phase transformation of pure metal will begin when it reaches the melting point, that is, $T_s = T_l$. If this happens, formula (5) will be meaningless. Therefore, a small temperature region $[T - T_\varepsilon, T + T_\varepsilon]$ will be constructed near the melting point to ensure the accurate iteration of the formula.

Although molten pool will appear after anode melting, the contact material is divided into liquid phase and solid phase, there is still energy exchange between liquid phase and unmelted solid phase in molten pool. The energy conservation equation of solid and liquid phase in unit of temperature is as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (k \nabla T) = 0$$  \hspace{1cm} (6)

3. Simulation Results and Analysis

The peak value of energy flow density on the anode surface is $1.19 \times 10^8$ W/m^2. The changes of anode contact temperature and molten pool are shown in Fig. 3 and Fig. 4 respectively. It can be seen from the figure that the anode surface temperature increases gradually from 0ms to 5ms, but it has not reached the melting point of the contact material. However, when it reaches about 5ms, the anode contact material has reached the melting point in the region with high temperature, and phase transformation begins, and obvious solid appears. When it reaches 10ms, the maximum surface temperature of the anode is 2560k, while the temperature at the back is only about 350k.

The influence of electrode rotation speed on anode surface temperature and molten pool formation is shown in Fig. 5 and Fig. 6. It can be seen from the figure that with the increase of electrode speed, the rising speed of anode surface temperature gradually decreases, and the time to reach the melting point of contact material is longer. When the electrode does not move, the molten pool is generated in
about 5ms, and the final temperature rises to about 2560k, and the bath depth starts to be stable at about 9ms, and the depth is about 0.55mm; when the electrode speed is 100r / s, the molten pool begins to form at about 7ms; at 10ms, the anode surface temperature is about 2200k, and the bath depth is 0.23mm; when the electrode speed is 200R / s, the anode surface temperature drops to 1600K, and the bath depth is 0.23mm. The molten pool was formed at 9ms near the melting point of contact material; with the increase of electrode speed, the surface temperature of anode decreased to below the melting point of contact material, and the change of temperature was not obvious, so there would be no molten pool.

The influence of electrode rotation speed on anode surface temperature distribution is shown in Fig. 7. It can be seen from the figure that with the increase of electrode speed, the maximum value of anode temperature gradually decreases, and the surface temperature distribution is more gentle. This is because with the rotation of the electrode, the cathode spot and arc plasma move together, so the energy flow density from arc plasma to anode is no longer It on only acts on a point, but acts on a larger area with the movement of the arc, which avoids the high temperature caused by the continuous inflow of energy flow density at a certain point; the plasma energy flow acts on different places, which can make the anode surface heated more evenly.
4. Conclusion
In this paper, a three-dimensional model of the thermal process of the anode contact of vacuum circuit breaker is established. Considering the phase transformation process of the anode contact material and the heat carried away by the evaporation metal vapor on the contact surface, the solid-liquid mixed region is treated by the description method of porous media, and the physical model of phase transformation process for the anode surface melting and evaporation is established. The results show that the rotating electrode is helpful to the breaking of vacuum circuit breaker.

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