

Low-Voltage Arc Interruption Computation: the Effect of Stefan Flow

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Abstract— Low-voltage circuit breakers provide essential protection for industrial and residential power distribution, by taking advantage of cathode drop to force current zero. This is accomplished by using the magnetic force and pressure on the arc as the contacts open to push the arc towards a stack of steel plates which break the arc into sub-arcs and thereby multiply the number of cathode drops. As the fault current can be high, substantial energy can be dissipated, which results in interactions among the arc and solid materials: ablation of wall materials. Comprehensive CFD/MHD studies have been conducted for arc running and splitting, although an important mechanism in arc breaking computation, the effect of Stefan flow induced by species generation, has not been considered. In this work, we report out a simulation approach for taking into account the effect of Stefan flow, particularly for the breakers with highly gasified wall materials. This approach accounts for the initial velocity of added-in species from the surface of the polymer wall and electrodes' surface, which will largely influence the flow field and the property of plasma mixture. The ability of conducting computation with considering Stefan flow effect will further enhances the accuracy of arc simulation in low-voltage circuit breakers.

I. INTRODUCTION

The function of low-voltage circuit breaker (LVCB) in power distribution system is to protect the electrical installations and control the power supply in the electricity network [1]. The LVCBs are designed to interrupt fault currents typically within half a cycle once the release mechanism is triggered. The contacts of most LVCBs operate in air, and the opening gap between the contacts increases from zero where the arc plasma starts to form. The initialized arc plasma inside the LVCBs will continue the fault current in the circuit, which is a great threat to the power system.

Many investigations aiming to study the arc plasma properties [2], simulate the arc motion and interaction with solid components [3] and interpret the arc physics [4, 5] have been conducted in the past decades. For example, Rong [3, 4, 6-9] has extensively studied the arc dynamics, wall ablation, metal evaporation, ferromagnetic effect of steels splitters, and conducted relevant experiments for validation. Rong et al. [9] modeled the metal vapor species by adding the mass source term in sheath layer, where the evaporation rate was derived from the energy balance in arc spot sheath. N Jeanvoine et al. [10] used finite element method to simulate the heat transfer and electrode melting at arc spot, and presented the estimation of temperature distribution in the arc spot. This work proposed

another approach to estimate the copper evaporation rate at arc spot with Langmuir free evaporation theory, however his calculation was confined within solid domain [10]. In 2009, Ma et al. [8] modeled the arc-wall interaction by applying the ablation at the boundary between the arc and the ablative wall, and concluded that polymer vapor can contribute to arc motion. To our best knowledge, neither metal nor polymer wall ablation in existing literatures has taken into account the Stefan flow effect.

If the housing of the LVCB is made up of polymers that are easily gasified in high temperature environment, large volume of polymer vapor will be generated which will tremendously increase the local pressure and accelerate the arc interruption. This technique is expected to speed up the arc splitting and shorten the duration of arc survival. To date, not much research related to wall ablation or ablative material development [8, 11] has been conducted. As a supplement to this topic, we propose to use surface reaction model with the effect of Stefan flow [12] for arc simulation. Stefan flow is internally generated and can be presented in the absence of any externally imposed flow. As the polymer vapor continuously and increasingly diffuses from the reaction surface to the ambience, such diffusion will result in a net transport of mass, a convection, which can be significant when intense rates of vaporization take place in hot environment, i.e., polymer wall ablation near the arc column. In this paper, we will consider the Stefan flow effect for wall ablation when solving the multi species transport in the LVCB model. Section II presents the LVCB model and methodology for arc simulation. The results are discussed in Section III, and the concluding remarks are given in Section IV.

II. METHODOLOGY

A. Simulation Model

Here, we consider a classical low voltage circuit breaker model, consisting of copper anode, copper cathode, steel splitters, ablation walls and air chamber. In general, the simulation model has 42 mm length, 25mm height and 4 mm thickness.

The interface between electrodes (splitters) and air are treated as sheath layer where voltage drops is applied along the thickness direction as shown in Fig. 1 (a). The mesh is densified near the sheath layer to capture large gradients of electrical field and temperature to avoid numerical instability.

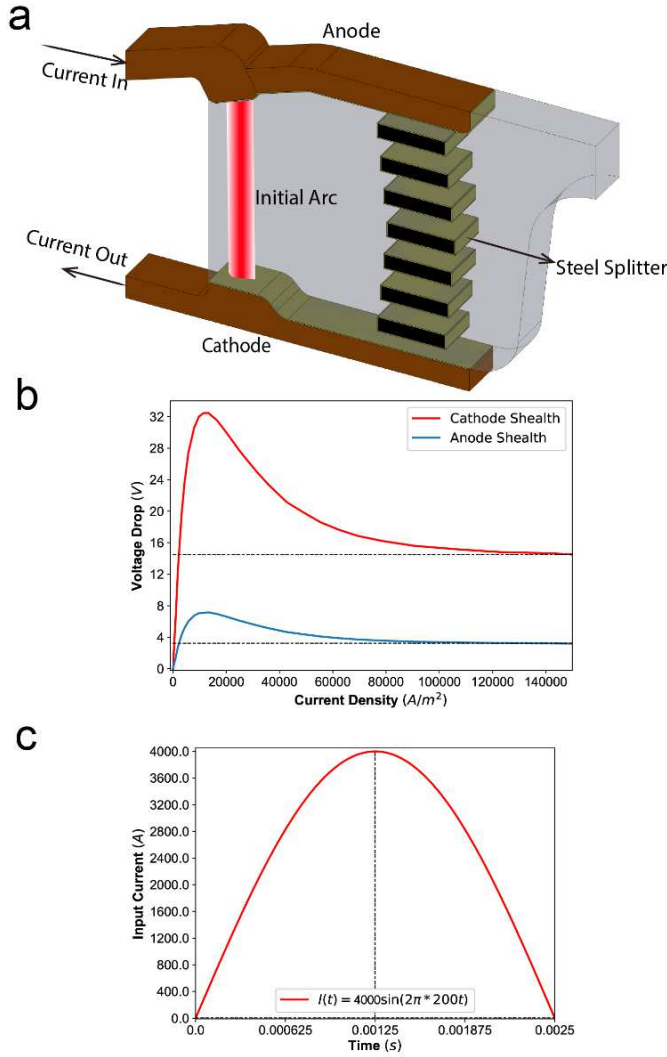


Fig. 1. LVCB model for arc simulation. (a) LVCB model geometry. The arc is initialized between the electrical contacts. (b) Cathode voltage drop curves as a function of local current density. (c) The input current waveform.

As shown in Fig. 1 (a), 200 Hz input current was applied on the surface labeled as Current In. The counterpart electrode marked as current out is earth grounded.

B. Mathematical Methods

In this study, the arc plasma is considered to be in Localized Thermal Equilibrium (LTE) condition except for the arc spot [13]. Modeling of arc in LVCB incorporates solvers for fluid motion, heat transfer, electromagnetics and surface chemical reaction, governed respectively by the Navier-Stokes equation, radiative heat transfer equation, Maxwell's equations, as well as rate and species transport equations. For LVCBs with wall ablation, multi species transport equations will also be considered and solved. In general, the results presented in this paper are obtained by numerically solving the aforementioned equations. Another set of important equations are required for solving electromagnetic fields (within low frequency range) involving magnetic vector potentials are:

$$\begin{aligned}\nabla \cdot (\sigma \nabla \Phi) &= 0 \\ \nabla^2 \vec{A} &= -\mu \vec{J} \\ \vec{E} &= -\nabla \Phi \\ \vec{B} &= \nabla \times \vec{A}\end{aligned}\quad (1)$$

where Φ is the electrical potential, $\vec{A}$ is the magnetic vector potential, and $\vec{B}$ is the magnetic flux density; $\vec{E}$ is the electric field, σ is the electrical conductivity, μ is the magnetic permeability. Based on energy balancing approach, the wall ablation rates R_{cu} are calculated by the following equations:

$$R_p = \frac{q_{rad} + q_{cond}}{h_{v,p}} \quad (2)$$

where q_{rad} and q_{cond} are the radiation and conduction heat fluxes to the ablation wall, respectively. $h_{v,cu}$ and $h_{v,p}$ are the latent heat for copper and polymer respectively. The computation is performed by commercial software ANSYS FLUENT, supplemented with user defined codes.

C. Arc Plasma Property

Under LTE, the local composition of the arc plasma is used to calculate the thermodynamic properties of the plasma mixture [9]. Here, we plot two curves, thermal conductivity and electrical conductivity, to illustrate that the polymer vapor concentration has a big influence on plasma mixture properties.

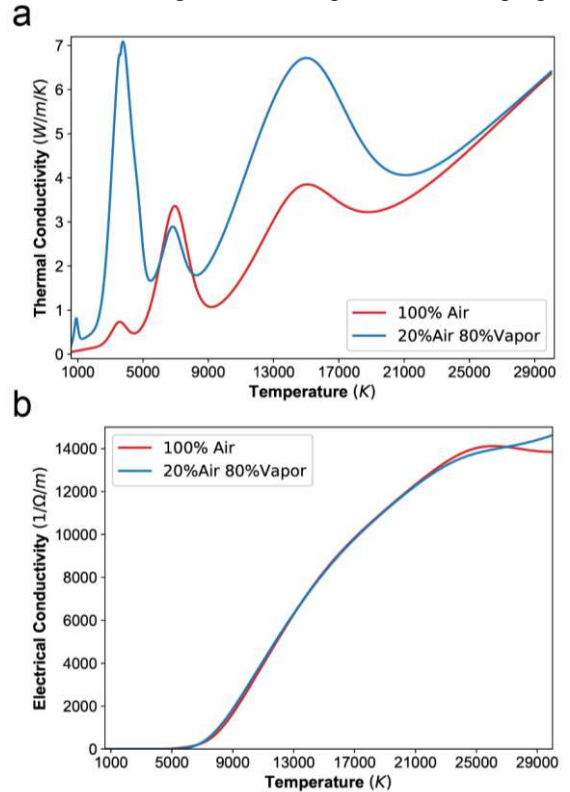


Fig. 2. Arc plasma properties for air containing different polymer vapor concentrations. (a) Thermal conductivity. The red and blue curve represents the thermal conductivity of pure air and mixture with 80% polymer vapor as a function of temperature. (b) Electrical conductivity.

From Fig.2, the species concentration plays an important role in the thermal conductivity for a wide temperature range, while

its effect on electrical conductivity becomes obvious when temperature is higher than 25000 Kelvin. Generally, the distribution of species is decided by the its generation rate and diffusion coefficient, while other important factor like convection can also have large impact on the species distribution due to laminar or turbulent mass flow, as discussed in the following section.

D. Effect of Stefan Flow on Species Transport

In any species transport system, depending on the operating condition, the transport can be dominated by either diffusion or convection. As is known, the species convection is usually driven by the externally applied pressure gradient. Another type of convection, called Stefan flow [12], is internally induced and can be presented in the absence of the external imposed gas flow.

To be specific, when generated from the substrate, the species produce a net mass flow, the convective flux. Magnitude of this convection flux depends on species generation rate and diffusion constant. Species generation rate is affected by local pressure, temperature and energy input etc. The diffusion constant is the D_i in (3), which can be complicated when take the temperature, multicomponent diffusion into account. In this work, we adopt a constant value for diffusion constant.

If the species diffusion coefficient and concentration gradient are known, the so-called Stefan flow velocity at the reaction surface can be analyzed from the species transport equation and expressed as [12]:

$$V_N = - \sum_1^n D_i \nabla Y_i / (1 - \sum_1^n Y_i) \quad (3)$$

where D_i is the diffusion coefficient for species i , Y_i is the species concentration, V_N is the velocity normal to the chemical reaction surface. To simulate the Stefan flow in the LVCB, the aforementioned momentum equations require no special modification because Stefan flow is self-contained. For example, after computing the reaction rate (or species generation rate), species flux can be deduced and applied to relevant surface.

III. RESULTS ANALYSIS

In this section, the simulation results will be discussed to illustrate the Stefan flow effect. The species concentration and projected flow velocity are plotted in Fig. 3. It is found that the species generation does amplify the velocity magnitude along the species concentration gradient as the Stefan flow effect.

From Fig. 3, the location of maximum of copper vapor concentration implies the arc spot where solid copper first melts and gasifies into vapor.

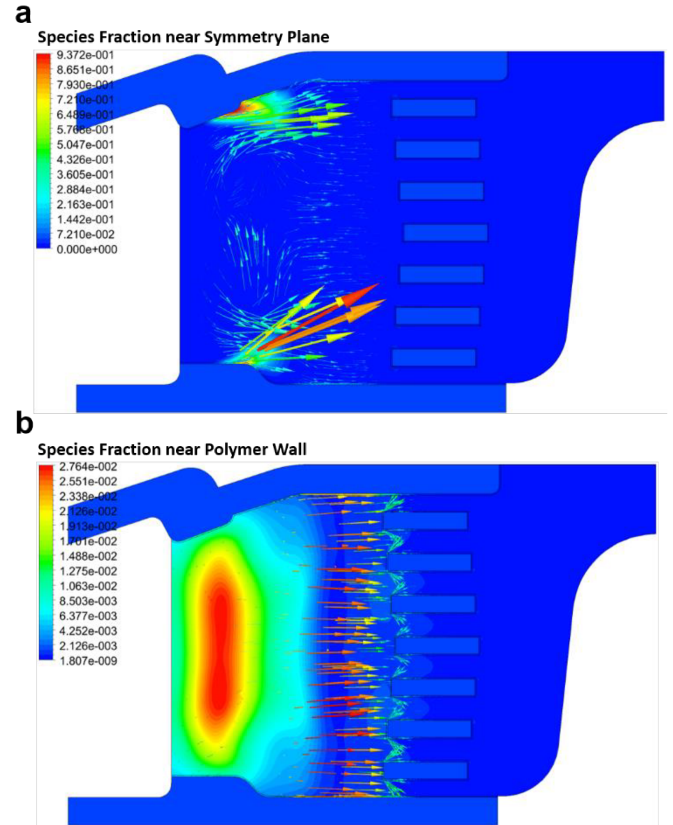


Fig. 3. Effect of species generation on flow field. The legend bar indicates the species concentration. The arrows denote the flow velocity, and its color and length represent velocity magnitude. Please note that the blue color of electrode and splitter does not correspond to the value in the legend.

The generation rate of species vapor can be very intense in real situation, and thereby augment significantly the local flow velocity and pressure. In return, the improved flow velocity will accelerate the species dispersion into ambience. The dispersed copper vapor will alter the electrical conductivity and radiation coefficient of plasmas mixture by orders of magnitude. Therefore, precise computation of the distribution of evaporated species stands a central role in high fidelity arc modeling. Since the polymer vapor concentration will greatly influence thermal conductivity in the mixture gas, and the surface area of ablation walls can be dozens of times larger than that of arc spot on electrodes surface. Thus, the generated polymer vapor can greatly alter the overall flow field and pressure field, which will carry and push the arc towards the steel splitters. And back-striking phenomena of arc will be less likelihood when great amount of the polymer gas is generated, which agrees with existing literature [8].

In short, Stefan flow enables the generated vapor to obtain initial velocity, and this initial velocity accelerates the species dispersion. Thus, the mixture properties, like electrical conductivity, thermal conductivity and radiation absorption coefficient, all will be updated appropriately and timely which in turn will impact the dynamics of arc motion and interruption. From another perspective, the ideal LVCB design will fulfill safe, thorough and robust arc interruption repeatedly. Wall ablation generates great amount of polymer vapor which

increases the local pressure, and subsequently the imbalanced pressure drives the arc movement, thereby expediting the arc extinction. When it comes to the metal evaporation on the electrode surface, the copper vapor will greatly influence the electrical conductivity, thus the current density will be increased as well (when a constant voltage boundary condition is applied). Consequently, the Lorentz force will be enhanced proportionally to drive a faster arc motion. In general, both the metal and polymer wall ablation play essential and positive effects on arc motion, as illustrated in Fig. 4.

Both the pressure field and the Lorentz force will push the arc towards right as expected. The current density and temperature profile are good indicators for proper simulation of real case arc in LVCB. The average current density can be found at around 10^7 A/m². The maximum current density is located at the arc spot on cathode surface, where the voltage gradient is the largest (across the cathode sheath). For the temperature field, the high temperature region is concentrated in the arc column where large amount of heat is generated by joule heating, with the maximum temperature slightly below 25000 Kelvin. The simulation results are in general agreement with literature data [1, 6, 7]. As shown in Fig. 4, the effect of wall ablation is clearly illustrated by the high pressure field on the left side where wall ablation takes place. The red and blue colors bound the arc column indicate clearly the magnetic self-pinching force, while the net Lorentz force is positive to drive arc movement to the right. (X axis points to right, as the arc motion direction).

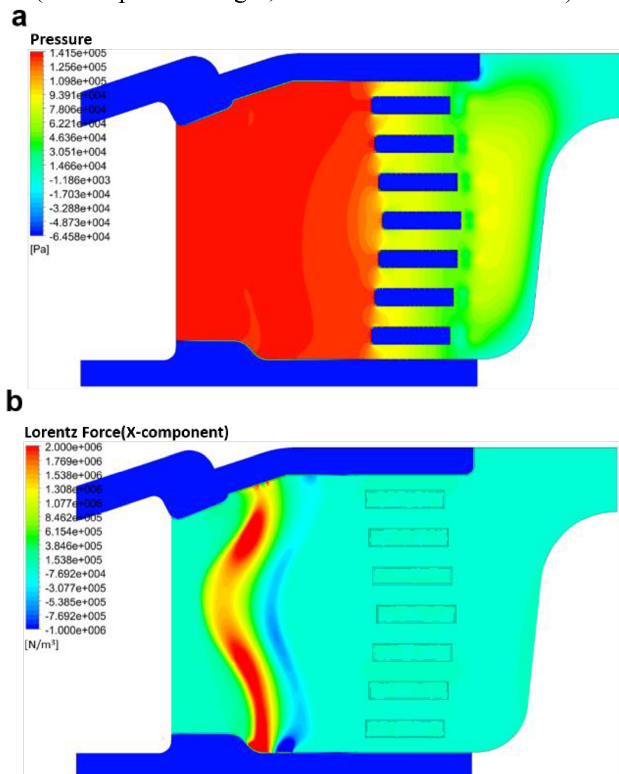


Fig. 4. Driving force for arc motion. The color of electrode and splitter does not correspond to the value in the legend. (a) The pressure field. (b) The contour of Lorentz force component.

IV. CONCLUSION

In this study, we perform arc dynamic computation in LVCB with fully implemented module to describe the effect of Stefan flow on species transport. The study suggests that the species generation by polymer ablation and/or metal evaporation has a profound influence on arc flow and interruption. It is revealed that the intensified flow field enhances the dispersion of species into arc column, and subsequently update the properties of plasma mixtures. Therefore, it is critical to include properly and accurately the generation and transport of species in arc simulation.

Besides, the great amount of generated species will influence the local flow field and pressure field, which helps to push the arc column towards the splitters and expedite the arc extinction. The Lorentz force can pinch and also drive the arc towards the splitters. As the fault current can reach thousands ampere, the Lorentz force can be outstanding and dominant in the arc motion. In general, effects of Stefan flow on the arc simulation are embodied in two aspects: One is to update the composition of plasma mixture dynamically and then affect the arc behaviors; another one is to accelerate the arc motion and expedite the arc extinction in LVCB.

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