

Experimental Study of Arc Discharge Induced Electrode Erosion and Its Influence on Arc Behaviors

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Abstract: Substantial energy dissipation in arc discharge results in strong wall and electrode erosion in a circuit breaker chamber, which largely alters arc plasma properties and thus affects the arc behaviors. Due to the strong vaporization rate, the generated vapor will give rise to a gas flow. Vapor flow and gas-dynamics will change the local partial vapor pressure, which in return adjusts the vaporization rate. The understanding of arc induced vaporization is of great importance to study dynamic arc behavior and the power interruption performance in circuit breakers, which however has not been fully studied. Significant progress has been made in the experiments and modelling of electric arc. Due to the surface ablation and metal erosion, a theoretical model needs to be established to estimate the influence of metal vaporization on the arc behaviors. In this work, we show the experiment of a low-voltage arc discharge and point out the most important factors that determines the metal vaporization rate, namely the discharge current. Beyond an explanation of the physical process of plasma induced erosion, we outline the general approach to study and model the arc induced metal vaporization.

Keywords: Circuit breaker, Electrode erosion, gas dynamics, Discharge current, Surface ablation.

1. Introduction

Electric arc discharge is one of the most popular research areas for many applications, such as plasma torches[1, 2], circuit breakers[3-8], arc welding[9], surface flashover and charge generation[10-13]. The arc roots on electrode surfaces features high current density and voltage drop[14]. Great amounts of electric energy released at arc roots will erode and vaporize the electrode materials, like copper. The copper vapor has a great influence on the thermodynamic properties of the plasma mixture. Preventing the stationary arc burning and erosion on the electrodes, accelerating the arc interruption is of great importance in power interruptions.

Many studies have been done to investigate the arc dynamic behaviors [15-17], arc-electrode interactions[18, 19] and electrode erosion[20-23]. The energy from an electric arc can be huge, because the electric arc generally happens under a fault-current condition. This energy dissipation includes heat conduction, thermal radiation, ionization and vaporization [22, 23]. In the arc root area, there are several types of energy like ion bombardment, electron capture and electron emission cooling etc.[24]. Some literatures[25, 26] present that the metal erosion rate should follow the Langmuir formula. The vapor temperature may be different from the electron temperature in the arc root area if considering the non-local thermal equilibrium [27, 28]. Besides, the conjugate heat transfer across the sheath based on the temperature field is another big issue, which is partially determined by the interfacial potential drop[29]. Therefore, the energy balance at arc roots should be used to estimate the power for erosion and vaporization[1]. The metal erosion induced by the electric arc is also investigated experimentally [30]. For the fault-current discharge arc, the current is high and the heat for vaporization can be significant [2, 31]. For low-current arcs, the metal vaporization is very small. Huo et al. [8] has proposed an arc root model which employs an structured hemisphere model for heat partition at the arc root and the

results well matches the experimental measurements. Another big problem in the arc interruption technique is the complicated arc root physics[29, 32], like voltage drop.

Since dielectric polymer has been used in the wall of circuit breakers. So, the polymer should be high-temperature resistive and can absorb considerable thermal energy (conduction and radiation) to instantly vaporize[33-36]. Huo et al. [8] proposed an approach of using Stefan flow to model the vaporization induced the gas flow, which helps to understand the wall-arc interactions. In addition, for each power interruption, the materials in circuit breakers suffers a temperature rise and fall, which can even causes an fluctuating thermal stress and fatigue problems[37] for the metals. Besides, if the vaporization happens in air, the vapor species will increase the local partial pressure, which in return will suppress the vaporization. On the other hand, the vaporization induced gas flow [3] is the process of species diffusion, which will alleviate the partial vapor pressure. In this paper, we will show the arc discharge experiment induced electrode erosion, and then discussed the general approach to estimate the arc induced erosion.

2. Model

We created an experimental model composed of two copper rods as shown in the dashed red frame within **Figure 1**. A damped L-C resonant circuit is used to generate high-current arc[3]. The energy stored in a capacitor bank, high voltage (HV), connected in both serial and parallel, is charged by a source and then discharged through a 1mH HV inductor for generating a current with a peak value of ~1200A. The arc voltage and current are recorded by a voltage and current transformer[3], respectively. A tiny copper filament connects the electrodes bottom for an easy arc discharge. When the sustained current increases to a moderate value, the copper filament will melt and vaporize, resulting in an instant arc formation. The thermal arc travels along the Jacobs' ladder

and extinguishes at the top.

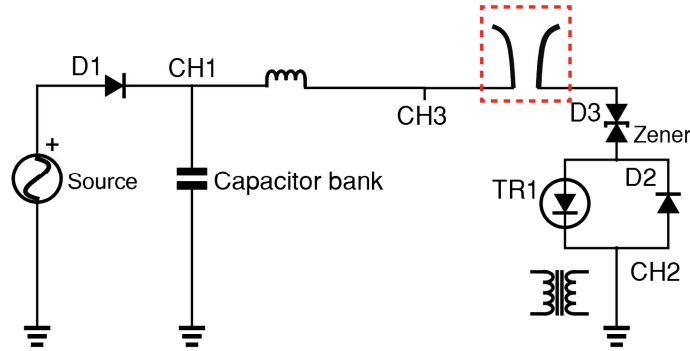


Figure 1. The model for thermal arc discharge. A L-C resonant circuit deigned for metal erosion experiment. The open-ended electrodes will be used to examine the metal erosion.

Due to the high pressure, the electric arc is neutral and in a quasi-equilibrium state. The transport properties of the plasma mixture are calculated by the Chapman-Enskog method [16, 38]. The thermodynamic properties of arc plasma are susceptible to the metal vapor species. Therefore, it is necessary to consider the copper vapor to update the plasma properties. Besides, the metal vaporization will absorb considerable heat, which prevents the further vaporization.

thermal arc moves under the combined effect of Lorentz force and thermal buoyance. For high-current discharge, like $\sim 1200\text{A}$ current, the Lorentz force is the major driving force for the arc movement. Due to the high current density and magnetic field near the arc roots, the arc roots move ahead of the arc column. The fast motion of the arc will pressurize the air in front of it. As a result, the high-current arc normally has a very irregular shape.

3. Results

The copper erosion spots are plotted in **Figure 2**. The

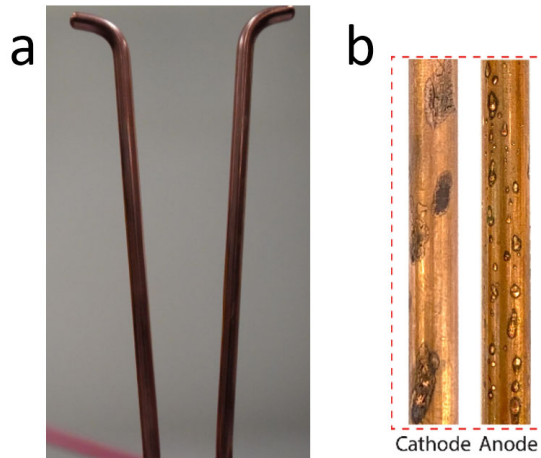


Figure 2. (a) the open-ended electrodes. (b). The erosion phenomena of the erosion spot. On the left is the cathode, and on the right is the anode.

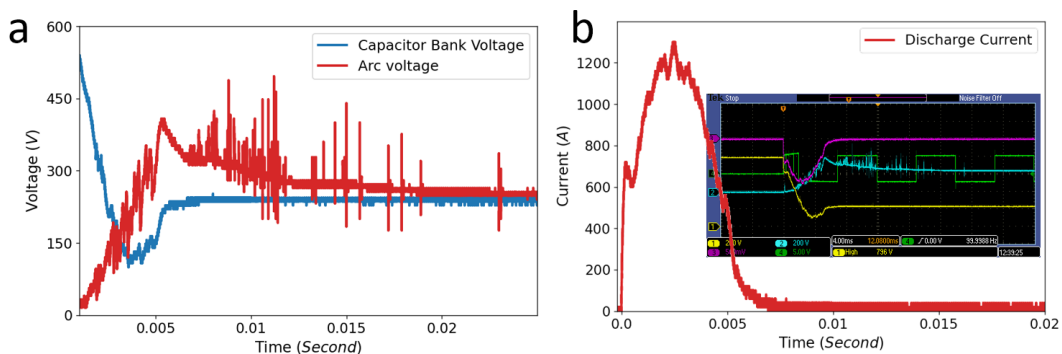


Figure 3. The discharge arc properties. (a) the measured voltage. (b) is the discharge current. From the inset, Channel 1 (yellow) is Capacitor bank voltage and Channel 2 (blue) is arc voltage and Channel 3 (purple) is the arc current, and Channel 4 (green) is the trigger Signal.

An interesting phenomenon is the arc jumping which is frequently observed in the arc discharge experiments[32]. The

maximum current density is located at the arc root areas which concentrates the energy injection, such as ion bombardment on cathode and electron capture in anode which will provide major heat source for the spot erosion.

The total discharge lasts about 10 milliseconds. And the discharge current surges to 1200A within 3 milliseconds, the initial arc explodes the fuse wire with the rapid increase of temperature. Before the arc discharge, the arc voltage is close to zero because the fuse wire connects the two electrode rods. During the capacitor discharge, the discharge gave rise to the high current and the fuse wire will melt and generate an arc, so the initial zero voltage will increase rapidly, which represents the arc voltage. After several milliseconds, the discharge is completed and then arc disappears. In other words, once the discharge current decreases to zero, the arc voltage measurement is stopped, and the left voltage signal from channel 3 represents the gap voltage.

So, one important problem is the erosion damage on the copper electrode caused by the electric arc as shown in **Figure 2**. The copper vapor concentration at the arc roots can be very high, which again increases partial vapor pressure. If the partial vapor pressure reaches the saturation pressure, it suppresses the vaporization. After generation, the copper vapor will diffuse into the ambient air. The erosion on the anode is overall more conspicuous than on the cathode. Due to the jumping, the erosion on the electrodes' surfaces is also discontinuous, as observed experimentally in **Figure 2**. Several other experimental trials show that under low-current high-voltage discharge, the electrode erosion is very small. This indicates the discharge current is the main factor that decides the energy for erosion, which indicates the voltage drop across the arc roots is close to a constant value.

4. Conclusion

The experiment of capacitor discharge was conducted to study the metal erosion in a pair of vertical electrodes. From the observation, the erosion spots on the anode are generally more severe and regular than those on the cathode. Since metal vapor has a great influence on the properties of plasma mixture, it is important to consider the electrode erosion in arc discharge. In addition, there is a positive relation between erosion spot size and arc power, and the erosion rate can be very high as the discharge is finished within several milliseconds. We found the arc power will first increase to a peak value and then decrease rapidly. Besides, the vaporization heat is negligible in low-current discharge but becomes remarkable under high current discharge. This indicates that the energy consumed by metal erosion and vaporization is decided largely by discharge current instead of the discharge voltage.

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