Cathode Arc Root Movement: Models Comparison

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Efficiency of the Low-Voltage Circuit Breaker (LVCB) goes through the fast movement of the arc from the contact to the splitter plates. Consequently, any complete fluid model of this process must allow the displacement of the electrical arc roots. In this paper, we will investigate the arc movement both experimentally and theoretically.

Keywords: thermal plasma modelling, low-voltage circuit breaker, LVCB, arc movement

1 INTRODUCTION

From contact opening to the arc splitting, current breaking in a Low-Voltage Circuit Breaker (LVCB) involves a large amount of physical phenomena. Thus, it is difficult to investigate each parameter independently in order to improve this device. Fluid modeling of the electrical arc behavior would be a powerful tool to access data that are not experimentally determinable and to identify the key parameters of arc breaking. Yet, correct assumptions need to be chosen regarding the arc physic.

The work presented here focus on modeling the arc movement on the rails using finite volume method and the commercial solver @Fluent. Two different boundary conditions enabling the arc roots displacement will be tested and compared with the experiment.

2 NUMERICAL MODEL

Our model is based on the work of the AEPPT team of the Laplace laboratory in Toulouse, France, which has long been studying thermal plasma modeling [1]. We use magneto-hydrodynamic approach to represent the electrical arc and it's interaction with the medium.

We assume that our plasma is a Newtonian fluid with a laminar flow. The medium is in local thermodynamic equilibrium. Evaporation of the walls is not taken into account and the plasma composition is pure air.

We don't model the arc ignition, which in the case of LVCB is the rupture of a molten bridge [2, 3]. Instead, a cylindrical channel is set in the middle of the geometry with a temperature of 18kK, allowing the current to flow from one electrode to another.

3 GEOMETRY AND BOUNDARY CONDITIONS

Since the arc chamber of a LVCB is very narrow there is a strong interaction between the thermal plasma and the walls. Thus the definition of the boundary conditions is of prime importance. For our simulation, we used a simplified geometry 20mm long, 8mm wide and 8mm high as seen in Fig.1. The mesh size is 0.1mm in the x direction and the time step is 5µs. This box is open at each extremity with atmospheric pressure (Exhaust in Fig.1). The arc moves between two parallel copper rails 1mm thick and 4mm wide. Those two solid volumes are modeled in order to calculate current distribution and energy transfer. They are separated from the fluid domain by the boundary conditions Rup for the upper rail and Rlow for the lower rail. Jin and Vout are respectively the currents inlet and outlet. The other boundary conditions are not shown in Fig.1 for clarity's sake but the walls have a fixed 300K temperature.

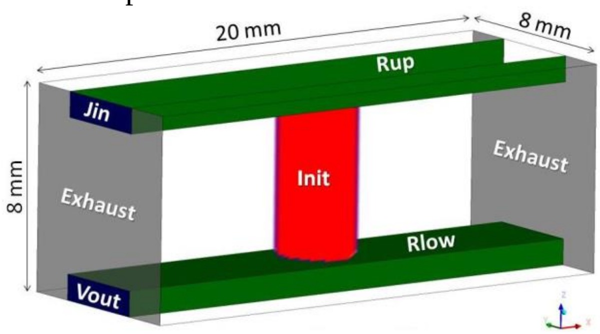

Fig.1: View of our calculation domain with the boundary conditions and the hot plasma channel (Init) for initialisation of the simulation, the medium is pure air with atmospheric pressure at the initial state

3.1 MAGNETIC BOUNDARY CONDITIONS

There are several methods to calculate the magnetic field [4]. In our case we use the potential vector formalism. This method is less time-consuming than Biot & Savart or Maxwell-Ampere and can be written in the general form of conservation equation allowing to use the same solver as energy and momentum equations. However, the boundary conditions must be chosen with care.

In order to obtain a correct value of the magnetic field with the configuration of a LVCB chamber we impose Dirichlet conditions for potential vector calculated for every boundary of the fluid domain using Biot & Savart.

The magnetic field is not calculated inside the arc runner but the current flowing inside the rails is taking into account for the Biot & Savart calculation.

3.2 METHOD A: BOUNDARY CONDITIONS

We first used a very simplified model where heat flow and electrical current through the electrode (boundaries Rup and Rlow in Fig.1) is calculated with diffusion equations only. This assumption neglects the sheath physics and the plasma/surface interaction. Yet, it allows the arc to move freely on the rail surface. Comparison with more detailed models would highlight the pertinence of developing more complex boundary conditions. A constant current density is imposed on boundary Jin to get the defined current and a null electrical potential is set on Vout.

3.3 METHOD B: BOUNDARY CONDITIONS

In this second method, a mean electrical conductivity around the electrode is computed and the arc root is set where the conductivity is the highest. For the cathode root, we impose on Rlow a current density profile and a temperature of 3500K inside a radius of 2.5mm around the specified position. Heat transfer between the plasma medium and the solid is not taken into account and temperature in the electrode is fixed at 1000K. In this work, we focus only on cathode displacement so the anode is treated with the same boundary conditions as in method A.

The difference with Swierczynski's work [5] is that the external magnetic field due to the current circulation in the rails is not treated separately with a rectilinear assumption but included with the boundary conditions as described previously in 3.1. Though rectilinear assumption reduces the calculation time, it is less adaptable to more complex configurations.

4 SIMULATION RESULTS

4.1 METHOD A: RESULTS

Even if both electrodes use the same boundary condition, the calculations show discrepancies between their behaviors. This is due to the enthalpic flux of the electrons, which cools the surface of the cathode. For lower currents (100A), it leads to a strong difference between the arc roots displacement, we can see in Fig.2 that the cathode (lower arc root) almost doesn't move.

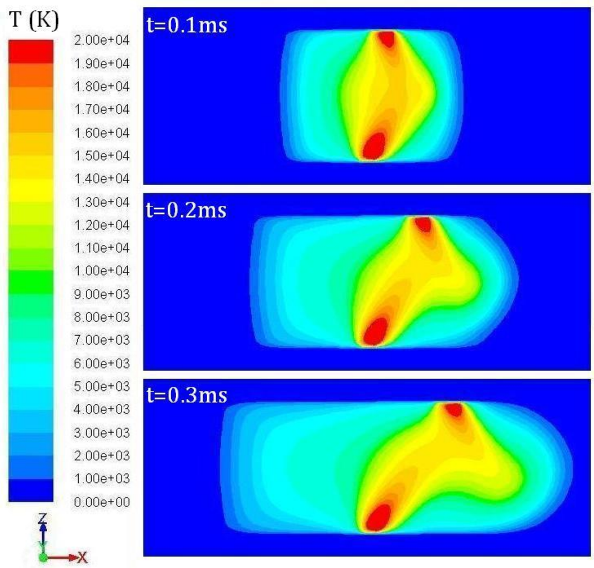

Fig.2: Arc movement and temperature with method A for a current of 100Adc in the simplified geometry presented in Fig.1

4.2 METHOD B: RESULTS

Compared to the previous simulation we changed the lower electrode (cathode) boundary conditions. The cathode is observed no longer immobile and moves at a speed close to the one of the anode. Since temperature and current density are controlled on the lower electrode, the maximum temperature of the cathode region is closer to the experimental results found in the bibliography [6].

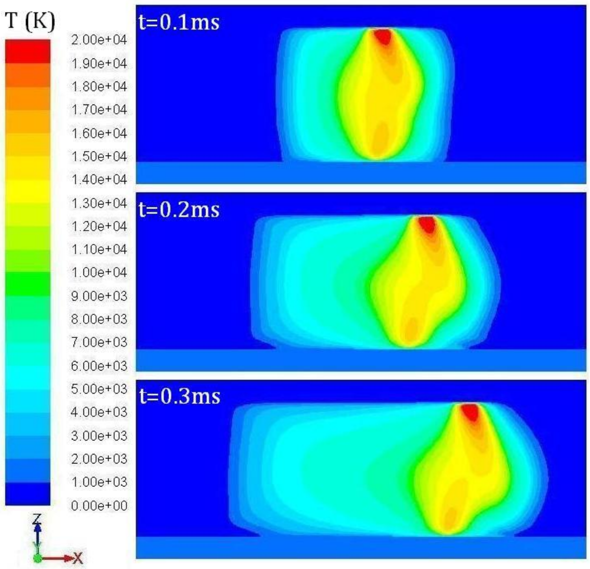

Fig.3: Arc movement and temperature with method B for the lower arc root (cathode) at current of 100Adc in the simplified geometry presented in Fig.1

4.3 COMPARISON FOR DIFFERENT CURRENT

We then used those two methods for direct currents of 100, 300 and 600A. The arc speed goes from 10m/s to 100m/s and is higher with method B as seen in Fig.4.

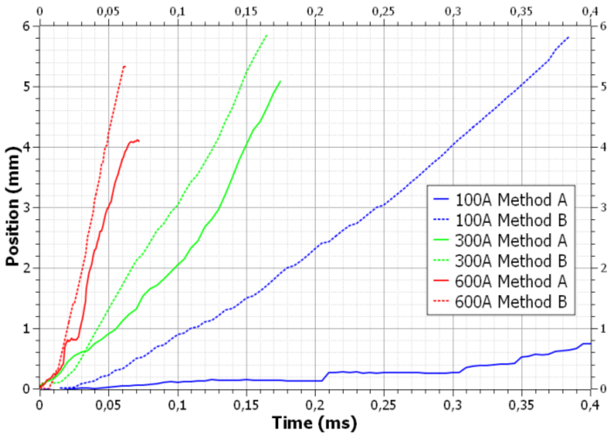

Fig.4: Cathode arc root movement for both methods and three different DC current in the simplified geometry presented in Fig.1

5 EXPERIMENTAL COMPARISON

In the meantime, experiments are carried out in order to confront our models. We build a test device to reproduce a simplified LVCB chamber where high speed imaging can be done. This experimental setup allows to reproduce an opening contact at a chosen constant speed but in the present study arc ignition is made with a fuse wire in order to get closer to the initial state of the simulation. Other parameters such as the materials used in the chamber and the size of the geometry can be changed. However, the experimental geometry is bigger than the numeric one. In fact, we reduced the calculation domain size in order to keep the simulation time low without degrading the mesh. Also, the experimental current is not continuous since the alimentation has been designed to reproduce à 50Hz fault current. For a peak current around 700A the experimental speed is around 20m/s. This is lower than the calculated speed but the exhausts are smaller in the experiment which should slow down the arc. Also the numeric geometry is smaller, with closer and smaller arc runners. Thus, external magnetic field should be more intense in the model, explaining why the calculated speed is higher than the experimental one. Anyway, we retrieve the basic arc shape and behavior.

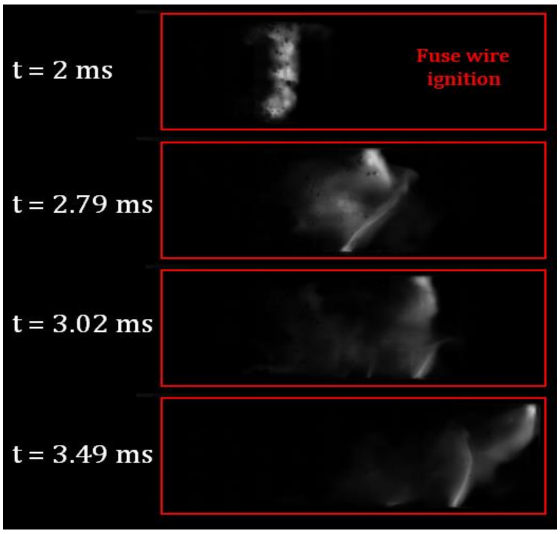

Fig.5: Movies of the arc movement at 100,000 frames per second in a 50mm long experimental geometry with 680A peak. The red box represents the size of the chamber.

Experimental evidences show that current can flow through several paths in the arc discharge with more than two arc roots, especially during arc commutation or restrikes. Therefore, method B seams unable to model correctly those events but adaptation can be done to define more than one arc root. Method A meanwhile does not allow any control of the current density and temperature of the arc roots which can reach overestimated values.

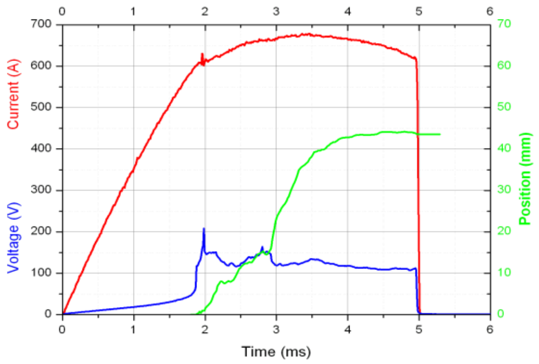

Fig.6: Measured current, voltage and global arc position calculated with the weighted mean of the light [7] corresponding to the test shown in Fig.5

6 CONCLUSION

Two methods to model the electrical arc movement have been compared. In method A, electrode material and fluid domain are coupled for the determination of the electrical potential and energy via diffusion equations only. In method B, we calculate a probable position of the arc root depending on the local mean electrical conductivity of the plasma medium. Then we set temperature and current density at this point [5].

Those methods give similar results for currents of 300 and 600A. For lower current, method A is unable to reproduce the arc root movement and method B seams more appropriate. On the other hand, the current density profile used with method B with a maximum value of 1.2e8 A/m^2 limits the level of current when the size of the arc root reaches the limit of the arc runner. Combined with the fact that there are often several arc roots on one electrode, method A may be more appropriate than method B to calculate arc displacement in a LVCB application.

However, since the method A boundary conditions give more degrees of freedom to the solver, convergence is harder and calculation time is longer with this method.

Comparison with the method developed by Karetta and Lindmayer [8] is an interesting perspective. Sadly, there is no description of the heat exchange at the electrode surface in their paper, leaving an uncertainty on the correct energy resolution to use.

To push this study further, calculations have to be done in numerical geometry with the same size as the experiment. Parametric studies could also be done with model and experimental means jointly but this requires much calculation time.

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