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NUMERICAL SIMULATION OF VACUUM ARC UNDER DIFFERENT AXIAL MAGNETIC FIELDS AND DIFFERENT EROSION RATES

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Abstract.

In this paper, we present a three-dimensional (3D) numerical model that describes a high current vacuum arc in the subsonic regime between copper contacts under the influence of an axial magnetic field (AMF). The model is based on a MHD approach to the inter-electrode plasma and is realized with the commercial software Ansys Fluent 19.2 with home made developments. Only the plasma region is modelled. The behaviour of the copper electrodes is taken into account by specific boundary conditions. We describe the model, the boundary conditions and present the simulation results. Temperature profiles and electron and ion densities will be presented in a reference case. Based on this arc modelling, a parametric study on arc characteristics will be performed, including varying the AMF strength, the ablation rate and the current intensity.

Keywords: plasma, numerical simulation, subsonic regime, vacuum circuit breaker.

1. Introduction

It is with a view to ecological transition that this study is being developed in order to reduce greenhouse gas emissions from circuit breakers and to comply with the environmental standards [**?**]. Siemens Energy is a central player in the field of electrical switching; the company develops high voltage circuit breakers (above 72.5 kV). In collaboration with the AEPPT team at Laplace laboratory, the company's objective is to study high-voltage vacuum arc breaking in order to develop its product range. Vacuum arc plasmas with an external axial magnetic field (AMF) have been successfully used in commercial vacuum switches for medium voltage (above 1 kV up to 52 kV included) distribution networks for several decades [1, 2]. Extending the technique of these switching arcs to high currents (several tens of kA) and high voltages (over 100 kV) is a technological challenge that requires the help of models. Improving the design and operation of vacuum switches depends largely on a good understanding of the physics of the vacuum arc. Over the last decade, the subject has received considerable attention, progress has been made in the physical modelling of vacuum arcs [3–7] and a large number of physical phenomena have been studied. Nevertheless, it is still difficult to conclude on the influence of each specific parameter and the basis of the model used is sometimes not well explained. Due to the hermetic configuration of the vacuum systems, it is difficult to account for the physico-chemical phenomena occurring within the plasma during arc extinction.

2. Numerical simulation

2.1. Configuration

We consider two flat, parallel copper electrodes of diameter $D = 5.5$ cm and spaced at a height $h = 1$ cm.

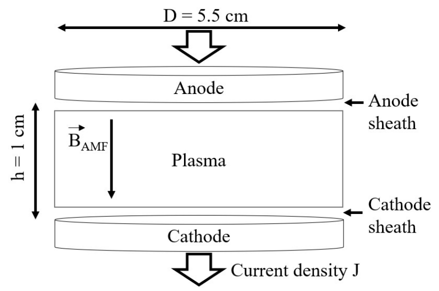


Figure 1. Schematic of the physical model.

The electrodes are in contact in a vacuum at the initial moment, outside the switching off process. During the electrical overload, the moving contact is moved by the operation of drive, an electric arc is established which burns in the vapours resulting from the erosion of the copper electrodes. The pressure is then of the order of some 10^{-3} Pa. This arc can adopt two operating states: the diffuse regime and the concentrated one (at high current intensities) [3]. To avoid constriction of the plasma column and heating of the metal contacts, it is possible to apply an AMF [8, 9]. This B_{AMF} field makes it possible to widen the current range in which the arc is in diffuse mode, i.e. stable in the inter-electrode medium, and to reduce the ablation of the materials. During the switching-off process, the particle flows have a helical motion and are directed from the cathode to the anode. This type of geometry is classically studied in the literature, the work of E. Schade [3] being one of the most complete. It mentions that two regimes are generally considered depending on the average current density at the cathode. If the current density is less than $3000\,\mathrm{kA/m^2}$, the flow is assumed to be supersonic and subsonic if the current density is higher than the given limit.

2.2. Equations

The mathematical and physical study of the behaviour of this medium is similar to that of a two-temperature plasma. The set of magneto-hydrodynamic equations that describe the arc in this configuration will be treated for two components, on the one hand the electrons and on the other hand the heavy particles (neutrals and ions) [3, 7]. The implementation of a three-dimensional numerical model describing the plasma medium as a two-temperature fluid will make it possible to predict the profiles of the temperatures, densities, pressures, and velocities of the heavy particles and electrons [4]. Today, the challenge is to be able to make the transition from a supersonic to a subsonic regime (at current densities above $3000\,\mathrm{kA/m^2}$). For the moment, the model in place only describes the subsonic in stationary regime. To understand the approach and the equations established to obtain the following results, it is necessary to be inspired by the work of Y.Langlois [4] and E. Schade [3].

2.3. Boundary conditions and hypotheses

Only the plasma part is described by the equations. It is not completely a vacuum medium because, due to the erosion of the cathode, the pressure increases rapidly. We assumed as in [2, 4] a laminar flow. The mean free path for interactions between charged particles of the same species (electrons-electrons, ions-ions) is always smaller (10^{-5} m for ions to 10^{-7} m for electrons) than the characteristic dimensions in the order of cm [4]. Under these conditions, the Kudsen K number is $K \ll 1$ for electrons and ions, corresponding to a continuous medium, so we use the fluid approximation for electrons and ions [10]. The contribution of the external AMF is imposed. According to the literature, a value of $5\,\mathrm{mT/kA}$ is generally used [3]. The electrodes are not really represented in the domain, but are taken into account by specific boundary conditions. As already mentioned, the plasma is a frozen mixture of ions and electrons with an average charge $Z = 1.9$ [11]. A two temperature model will describe this medium.

The particles in the plasma medium come from the erosion of the cathode. The cathode is therefore considered as a mass flow inlet. In the work of E. Schade [3], this ablated area (corresponding to the inlet) represents 75 % of the surface while the remaining 25 % on the cathode side is considered as unablated. In our case, as a first approach, we consider that the ablation is governed by a Gaussian profile imposed on the whole electrode. It is set so that the value of the profile on the cathode edge is close to 10 % of the value of the axis. As explained earlier, depending on the value of the current density, the flow will be considered subsonic or supersonic. In our case, as proposed by E. Schade [3], we assume that the electron and ion temperatures are the same $T_i = T_e = 34800\,\mathrm{K}$. A copper flux is imposed with a specific value of $50\,\mathrm{\mu g/C}$. An ablation profile and the current density profile are directly related. The Gaussian profile is therefore also used for the current density. As the self-induced magnetic field is calculated from the potential vector equations, closed by the Biot and Savart boundary condition, the current density inside the cathode is required, and this same Gaussian profile is used.

The anode collects the plasma flows. We consider the anode with an output pressure condition as proposed by Y. Langlois [4] and presented in figure 2. We assume the anode collects the plasma flows and the previous equations are used to find the exit pressure between the pre-sheath (ps) and the plasma. The velocity of the ions in the sheath (s) is assumed to be equal to the Böhm velocity and this velocity is constant in the pre-sheath. A space charge zone with a potential drop tends to adjust in order to regulate the flow of electrons collected at the anode. The pressure of the ions at the exit of the pre-sheath is to be calculated. Finally, the outlet pressure corresponding to the total pressure is calculated as a function of the ion velocity.

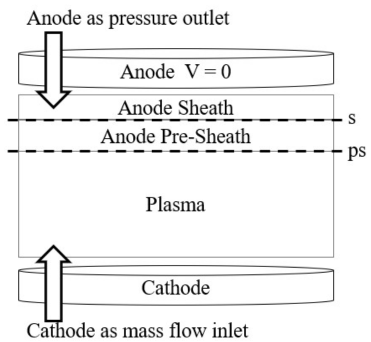


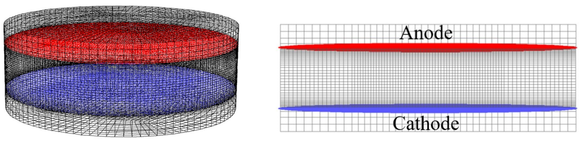
Figure 2. Diagram of the physical model with annotations of the boundary conditions.

This calculation strategy comes from Y. Langlois's thesis applied to our configuration [4]. First, we calculate the conservation equation of the energy of the ions in the pre-sheath. Then we calculate the ion density equation in the pre-sheath by the Boltzmann factor. Finally, we establish the law of conservation of mass through the pre-sheath. By linking these relationships we can deduce the exit pressure by assuming that the Böhm velocity is constant in the pre-sheath. From this combination, assuming that the velocity inside the duct is the Böhm velocity, we deduce the outlet pressure. It should be noted that it is not obvious how to re-demonstrate Y. Langlois' proposal, as it only works if the Böhm velocity is assumed to be constant in the pre-duct. Nevertheless, this assumption seems reasonable.

2.4. Simulation results and discussion

2.4.1. Vacuum arc modelling

The electrodes and the inter-electrode space are represented by a fine mesh as shown in figure 3 a), of 280000 cells, with a step of 0.1 mm in the vicinity of the electrodes and a step of 0.05 mm in the middle. The results obtained by ANSYS Fluent 19.2 software in home made developments [12], will be presented on a frontal section plane to facilitate their understanding. In figure 3, we observe the mesh of the system with the anode (in red) at the top and the cathode (in blue) at the bottom. Radiation phenomena have a major influence on the results. Nevertheless, we do not take radiation into account due to a lack of data. Existing data on radiation are calculated on the basis of E.T.L. assumptions and for temperatures up to 35 kK. The data range is therefore not in line with the temperatures reached in the model (up to 70 kK for electrons), and the medium shows deviations from equilibrium. The use of these existing data is therefore not really appropriate The data are presented without taking into account the radiation and in a stationary state.



(a) (b)

Figure 3. (a) 3D mesh of the physical model, (b) 2D face plane of the mesh used to represent the simulation results.

2.4.2. Reference case

First simulation results of the vacuum arc in subsonic regime and in stationary in the inter-electrode space are presented. The case used in the 2003 paper by E. Schade and D.L. Shmelev [3] is our reference for this study whose characteristics are given in the table 1.

From the numerical calculations we first obtain the temperature profiles of the electrons and ions in the inter-electrode space, and then the corresponding particle densities presented in figure 4.

The temperature simulation results indicate that the maximum reached by T_e is $7.1{\times}10^4$ K which is a relatively high value compared to the literature (around 4.3×10^4 K [3]) and which we seek to understand. The important thing here is to realise the impact of some parameters on the physics of the arc. The electron and heavy densities are consistent with the literature results and are close to the cathode with values of $n_e = 1.53 \times 10^{16}\,\mathrm{cm}^{-3}$ and $n_i = 8.26 \times 10^{15}\,\mathrm{cm}^{-3}$.

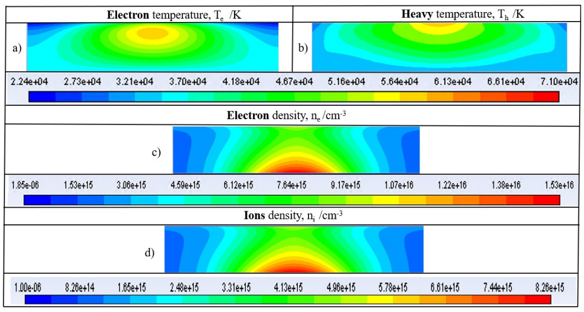


Figure 4. Fields of temperature and electron and ion densities in the reference case.

2.4.3. Parametric study

It will also be interesting to look into influence of the variation of the ablation rate, the strength of the AMF and the current intensity on the metal vapour plasma. Figure 5 shows the ion density of the plasma for an ablation rate of 50 and 115 µg/C [8]. This variation corresponds to an increase in the amount of metal vapour in the vacuum chamber. As a result, the amount of Cu^{+} and Cu^{++} ions is higher and the number of collisions between charged particles increases. We also expect the temperature to increase with ablation. However, quantifying the proportion of ablation in a vacuum arc is relatively complex, especially the method of estimating the electrode material losses.

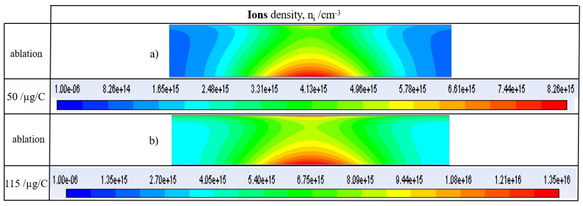


Figure 5. Fields of the ion density for an ablation rate of a) 50 µg/C and b) 115 µg/C, $I = 15$ kA, $B_{AMF} = 75$ mT.

Figure 6 shows the temperature profiles of the electrons and heavy particles for several values of AMF, 75 mT and 125 mT. The higher the AMF, the more the arc constriction will be attenuated, resulting in a more homogeneous distribution of the ion density in the plasma.

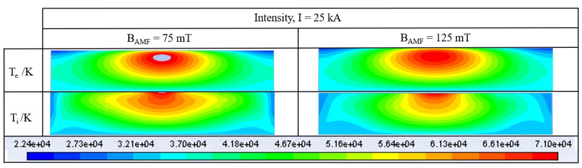


Figure 6. Fields of the electron and ion temperature for several values of the axial magnetic field, B_{AMF} =75 mT and B_{AMF} = 125 mT , $I = 25$ kA, the ablation rate is 50 µg/C.

The current intensity and the AMF magnitude have a direct impact on T_e and T_h as can be shown in

Intensity /kA	Axial magnetic field /mT	Ablation rate /µg/C	Limits conditions
15	75	50	$T_e = T_i = 34800\,\mathrm{K}$

Table 1. Characteristics of the reference case.

figure 7. There is an increase in electron temperature of about $\delta T = 2.4 \times 10^4\,\mathrm{K}$ between 15 kA and 25 kA.

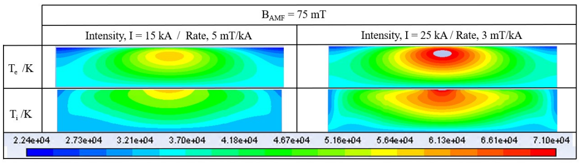


Figure 7. Fields of the electron and ion temperature for several values of current intensity, $I = 15\,kA$ and $I = 25\,kA$, $B_{AMF} = 75\,mT$, the ablation rate is 50 µg/C.

The value of the current intensity will also have an impact on the physical components of the system, such as the temperature of the electrons and the heavies, see figure 8, with rate of 5 mT/kA for parametric study of influence of AMF.

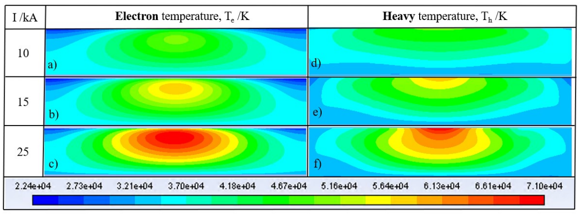


Figure 8. Fields of electron and ion temperature for several values of current intensity $I = 10\,kA$ and $B_{AMF} = 50\,mT$, $I = 15\,kA$ and $B_{AMF} = 75\,mT$, $I = 25\,kA$ and $B_{AMF} = 125\,mT$, ablation rate is 50 µg/C, rate is 5 mT/kA.

Whether electrons or ions, there is a significant increase in T_e and T_h with the value of the current intensity. This is due to the higher collisional energy transfer between the charged particles. The problems encountered in this simulation of the arc are still numerous, in particular the one related to the values reached for the temperature. The high temperature values are probably due to the fact that radiation is not taken into account, as it is a complex component to calculate.

3. Conclusion

The simulation behaviors are consistent with the literature in a subsonic and stationary arc mode. The supersonic mode needs to be developed as well as the transition between the two regimes. Studies need to be carried out on the contribution of radiation and electrode ablation. A more complex geometry should be considered so that the results can be closer to reality. We will also try to vary the inter-electrode distance by a few centimetres to observe its impact on plasma parameters.

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