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INFLUENCE OF COPPER VAPOURS IN SF_6 PLASMA

P. Freton[a,*], J-J. Gonzalez[a], A. Harry Solo [a], F. Reichert[b], A. Petchanka[b]

[a] *Laplace, UMR 5213 CNRS-UPS-INP, Université Paul Sabatier 118 rte de Narbonne, bat3R2, 31062 Toulouse Cedex France*

[b] *Siemens AG, E T HP CB PLM RD B PB, Nonnendammallee 104, 13629 Berlin, Germany*

[*] freton@laplace.univ-tlse.fr

Abstract. In this study a theoretical approach allows estimating the ablation mass flux of copper from a corrected Hertz-Knudsen flux. The influence of the copper vapours coming from the anode electrode to an SF_6 plasma is studied in a simplified 2D configuration. Depending on the plasma pressure an ablation or a diffusion state is considered. The amount of copper versus time is presented. An RMS current $I = 10\,\mathrm{kA}$ is applied leading at $t = 10\,\mathrm{ms}$ to an amount of copper equal to 0.55 mg. The vapours change the plasma properties mainly the electrical conductivity and radiation and so the plasma behaviour. At time $t = 5\,\mathrm{ms}$ the electrode erosion leads to a copper plasma. This simple case shows the necessity to well consider the copper erosion in plasma modelling as in High Voltage Circuit Breaker (HVCB) where higher current are considered.

Keywords: Copper ablation, High Voltage Circuit Breaker, Electric arc.

1. Introduction

In HVCB modelling, ablation of electrodes is rarely taken into account whereas in reality, at high current it could be an important process. Modelling such ablation is quite complex due to numerous mechanisms involved. In this paper, an approach is proposed to represent this phenomenon. In a first part, the basis of the ablation model are discussed. Then a magneto hydrodynamic model and the specific source terms due to the ablation are presented. A "simple" geometry is used to test this new model. Results show a strong presence of copper within the plasma even with a small part of the electrode ablated. The vapours should change strongly the properties of the plasma and then the importance of mechanisms involved in the HVCB.

2. Theory

2.1. Ablation model

When an electrode is submitted to the heat and radiation fluxes coming from the arc, its temperature can increase and then ablation occurs. The description of the ablation process is quite difficult to describe and depends on the pressure vapour P_{vap} of the ablated metal. In our case, metal is copper. P_{vap} is given in (1). It depends on the surface temperature T_{s}, the temperature of vaporisation of the metal T_{vap}, the mass of the metal particle m_{Cu} and its heat of vaporisation L_{vap}, k_{b} is the Boltzmann constant.

$$\frac{P_{\mathrm{vap}}}{P_0} = \exp\left(\frac{L_{\mathrm{vap}}\, m_{\mathrm{Cu}}}{k_{\mathrm{b}}}\left(\frac{1}{T_{\mathrm{vap}}} - \frac{1}{T_{\mathrm{s}}}\right)\right) \quad (1)$$

Depending on the pressure of the plasma P_0 two different cases have to be considered:

- ☐ Case 1: The "diffusion case" where $\frac{P_{\mathrm{vap}}}{P_0} \leq 1$
- ☐ Case 2: The "ablation case" where $\frac{P_{\mathrm{vap}}}{P_0} > 1$

In the first case, the temperature of the surface T_{s} is under the temperature of vaporisation of the metal T_{vap}. Then, the surface is in equilibrium with the plasma and metal vapours diffuse from the surface to the plasma. The mass fraction of copper on the surface can be calculated from equation (2). M_{Cu} and M_{Pl} are repectively molar mass of copper and plasma.

$$\omega_{\mathrm{Cu}} = \frac{P_{\mathrm{vap}}\, M_{\mathrm{Cu}}}{P_{\mathrm{vap}}\, M_{\mathrm{Cu}} + (P_0 - P_{\mathrm{vap}})\, M_{\mathrm{Pl}}} \quad (2)$$

In the second case, an ablation process occurs. Semenov [1] explains that in this situation, a strong flow of copper vapours goes away from the surface and that, close to the surface, the vapour is no more in equilibrium in the plasma. Indeed, a Knudsen layer appears where the distribution function of the vapours is no more Maxwellian. This layer is followed by another one in overpressure (compared with the one of the plasma) but in equilibrium. Semenov [1] has proposed a 1D approach to describe the phenomena of ablation in this context in order to obtain the ablated mass flux Φ_{Cu} (kg/(m^2·s)) of copper and also the mean velocity of the copper flow in the plasma v_{Cu}. Even if this approach is very interesting, its implementation is difficult. Benilov [2] proposes another approach which consists to estimate the ablation mass flux of copper as proportional to the Hertz-Knudsen flux Φ_{HK} (3)

$$\Phi_{\mathrm{HK}} = P_{\mathrm{vap}} \sqrt{\frac{m_{\mathrm{Cu}}}{2\pi k_{\mathrm{b}} T_{\mathrm{s}}}} \quad (3)$$

Then copper mass flux is given by equation (4) where α_v can be calculated from material and plasma data (see [2] for more details).

$$\Phi_{\text{Cu}} = \alpha_v \, \Phi_{\text{HK}} \tag{4}$$

We compared the two approaches which lead for copper to the same results [3] for the ablation mass flux. In his article, Benilov estimates the velocity of the particles coming inside the plasma from the ratio of the mass flux to the density at the edge of the Knudsen Layer n_∞ as reported in equation (5).

$$v_{\text{Cu}} = \frac{\Phi_{\text{Cu}}}{m_{\text{Cu}} \, n_\infty} \tag{5}$$

2.2. The magneto hydrodynamic model

2.2.1. geometry

To analyse the results, and to study the influence of the copper vapours, we have used the geometry given in Figure 1. The geometry is axisymetric with axis AI. In the upper part, AB is an electrode considered as an anode. BC and HI are pressure inlet/outlet, CDEFGH are walls.

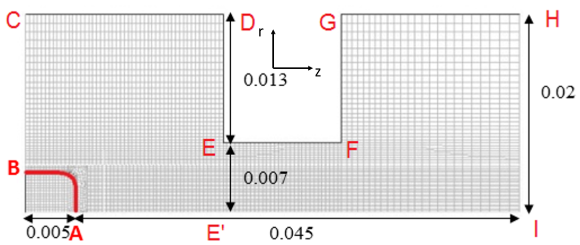

Figure 1. Geometry used for the simulation (dimensions in m).

2.2.2. Hypotheses

We assume that the configuration can be describe in two dimensions (2D) with an axis of symmetry. The top electrode is pure copper. As the problem is 2D, a porous electrode located on segment (EE') is used. The fluid is assumed to be Newtonian and laminar, the gas is SF_6 with copper (coming from the electrode) and the plasma is assumed to be in Local Thermal Equilibrium (LTE). The problem is transient.

2.2.3. Equations

In order to describe the arc fluid model the Navier Stokes equations are solved coupled with the mass and energy conservation equations. All these equations can be written in the form of the generalized conservation equation (6).

$$a \, \frac{\partial}{\partial t}(\rho\phi) + b \, \nabla \cdot (\rho \vec{v} \phi) = \nabla \cdot \big(\Gamma \nabla(\phi)\big) + S_\phi \tag{6}$$

For the fluid, the equations solved are mass conservation, momentum equations for axial and radial velocity v_z and v_r, energy conservation for enthalpy h and then temperature T. The equation for the mass fraction of SF_6, ω_{SF_6}, is solved and mass fraction of copper ω_{Cu} deduced. Thermodynamic and transport properties of pure SF_6 and copper are used and Wilke laws [4] are applied to obtain the mixture properties. Electrical properties of the plasma (current density $\vec{j}$, magnetic field $\vec{B}$) are obtained repectively from the equation for electric potential V and potential vector components A_r and A_z. The radiation of the plasma is treated by Discrete Ordinate method on 7 bands where mean absorption coefficient of SF_6 and copper have been pre-calculated. This enables to obtain the radiative flux and its divergence. Additional details on the equations set and boundary conditions can be found in previous papers [5–7]. With copper vapours, specific source terms for ablation model have to be taken into account. Furthermore, the copper vapours coming from the electrode are transported in the plasma. In the real case, they can re-solidify when the gas temperature becomes lower than the one of vaporisation. If this condition occurs during calculation, we assume that copper is re-solidified and that it disappears from the fluid part. The following source terms are then written for ablation model and re-solidification of copper:

- ☐ Source term in the equation of mass conservation. For the mass conservation source term S_m given in equation (7) is used in order to take into account the exiting vapours at low temperature from a surface S of normal $\vec{e}_s$ close to a cell of volume V_{cell}. Losses of copper in the volume are described by the second part of the equation.

$$S_m = \beta \left[\frac{\Phi_{\text{Cu}} \, S}{V_{\text{cell}}} \right] - \alpha \left[\frac{\omega_{\text{Cu}} \, \rho_{\text{Cu}}(T)}{\Delta t} \right] \tag{7}$$

  With $\alpha = 0$ if $T > T_{\text{Vap}}$ and 1 otherwise. Δt is the time step of the simulation. β is equal to 1 in the layer close the electrode ~ 0.1 mm, 0 elsewhere.

- ☐ Source terms in momentum equations. It is necessary to take into account the momentum of vapours flowing from the anode surface to the plasma. The source terms of equations (8) and (9) are used. Resolidification of copper leads also to a decrease of momentum in the fluid domain (second part of the equations)

$$\begin{aligned} S_{v_z} = \beta & \left[(\rho_{\text{Cu}}(T_{\text{vap}}) \, v_{\text{Cu}} \, \vec{e}_s \cdot \vec{e}_z \right] \\ & -\alpha \left[\omega_{\text{Cu}} \, \rho_{\text{Cu}}(T) \, v_z \right] \end{aligned} \tag{8}$$

$$\begin{aligned} S_{v_r} = \beta & \left[\rho_{\text{Cu}}(T_{\text{vap}}) \, v_{\text{Cu}} \, \vec{e}_s \cdot \vec{e}_r \right] \\ & -\alpha \left[\omega_{\text{Cu}} \, \rho_{\text{Cu}}(T) \, v_r \right] \end{aligned} \tag{9}$$

- ☐ Source term for energy equation. Concerning the vapours arriving in the plasma, we assumed that if their enthalpy is lower than the plasma one, they are pre-heated in the anode sheath by collisions with the electrons and by radiation. If this is not the case, they are injected with their enthalpy at the temperature of vaporization (It should be underlined that in the reference energy of the system, enthalpy of copper gas should contain L_{vap} for temperatures over T_{vap}). This assumption has a consequence on the energy balance at the anode. This point will be presented in the next paragraph. Then, the energy source term can be estimated from equation (10). h_{mean} is the mean enthalpy of the plasma in the layer close to the electrode. If only one cell is present in the layer (as in our geometry) this is the enthalpy of the plasma in this cell. It depends on temperature T, pressure P and mass fraction ω_{SF_6} of SF_6. The second part concerns the "resolidification" of the copper if temperature decrease under the temperature of vaporisation

$$S_{nrj} = \beta \left[\frac{\Phi_{Cu} S}{V_{cell}} \mathrm{Max}\big(h_{mean}, h(T_{vap})\big) \right] - \alpha \left[\omega_{Cu}\, \rho_{Cu}(T) \left[h(T_{plasma}) - h(300\,\mathrm{K}) \right] \right] \quad (10)$$

2.2.4. Modelling of the anode

The anode is made of copper. Properties function of temperature for thermal conductivity, mass density and specific heat are used [8]. We don't take into account the liquid copper movements but liquefaction of copper is taken into account by adapting the specific heat close to the liquefaction temperature T_{liq}. Radiation emissivity of copper given by [9] is used.

In the electrode, electric potential and vector potential equations are solved.The source term of Joule effect is taken into account. In order to model the anode, we use the assumption proposed by Lowke and Tanaka [10]: a small layer of 0.1 mm with an electric conductivity of 10^4 S/m is used in the sheath. The energy flux at the anode surface is given in equation (11) where $q_{cond,plasma}$ is the conduction flux from the plasma, q_{rad} the radiation flux estimated from DOM method, W_{Cu} the electron work function of the copper. No voltage in the sheath is considered and depending on the case it can be as positive as negative. In the energy flux on the anode, the heating of vapours coming from anode to plasma is taken into account. On the surface, this flux is balanced by the conduction flux towards the anode.

$$q_{anode} = q_{cond,plasma} - q_{rad} + \frac{\vec{J}\cdot\vec{e}_s}{e} \left[\frac{5}{2} k_b \left(T_s - T_{plasma}\right) + W_{s,Cu} \right] - \Phi_{Abl} \left[h(T_{vap}) - h_{mean} + L_{vap} \right] \quad (11)$$

2.2.5. Parameters for the calculation

The problem is solved by Ansys Fluent software. Specific User Defined Subroutines have been developed for taking into account plasma characteristics [7] and the interaction with the anode. The imposed current density is a half wave sinus curve, with a period of 10 ms, and a maximum intensity equal to 10 kA. The time step for the calculations is $\Delta t = 10\,\mu s$.

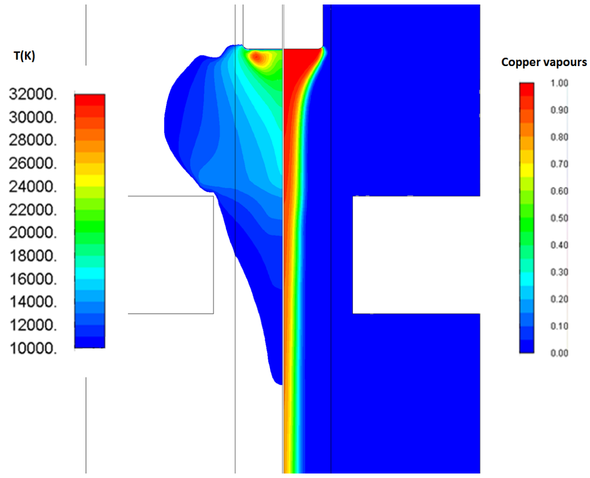

Figure 2. Temperature and copper mass fraction for time t=5.2 ms.

3. Results

3.1. Temperature and copper mass fraction

Temperature and mass fraction fields obtained at time $t = 5.2$ ms are presented in figure 2. Concerning mass fraction, we can observe that, at this time, the whole core of the plasma is composed of pure copper. The temperature is quite high with a maximum around 30 kK. One can observe that this maximum is located out of the axis, close to the corner of the electrode. This effect is due to the current path which occurs preferentially on the electrode corner. To verify this point, the current density vector is plotted in figure 3. Where the current density is maximum, the Joule effect is high leading to the out of axis maximum of temperature. This out of axis maximum could sound strange but similar situation can be reported in MIG welding configuration where there is a strong presence of metal vapours in the center of the plasma [11]. This shows the importance of well describing the current path from the electrode to the plasma.

3.2. Ablation process

Another interesting field to plot is the mass source term due to copper ablation. It is plotted in figure (4) with the temperature in the anode. At this time, the temperature is high close to the electrode surface in contact with the plasma and propagation within the electrode can be observed. Nevertheless, only the corner of the electrode is over the vaporisation temperature which leads to ablation (case 2 $\frac{P_{vap}}{P_0} > 1$). The amount of copper coming from the ablation is then located very close to this corner. Nevertheless it is interesting to observe that the copper has propagated in the whole core of the plasma, changing its properties compared to pure SF_6.

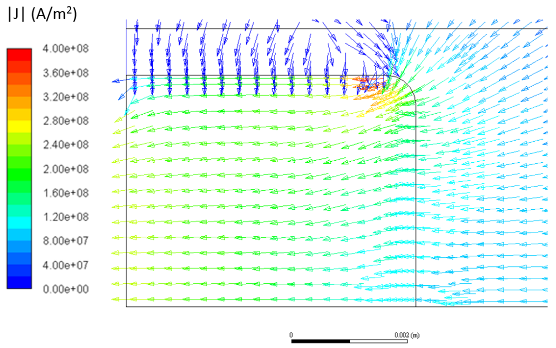

Figure 3. Current density vector close to the electrode for time t=5.2 ms.

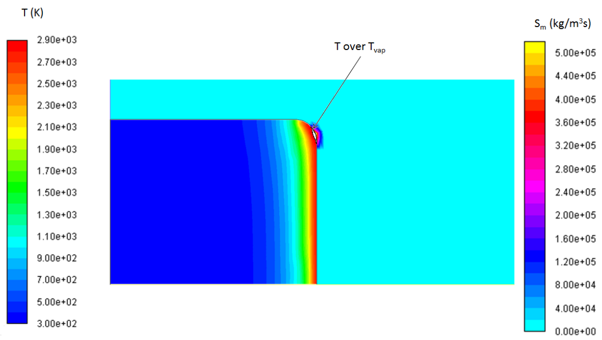

Figure 4. Temperature in the electrode (left) and mass source term due to copper ablation (equation (7)) at t=5.2 ms.

The calculated case leads to an energy injected of 5.3 kJ. For this energy the amount of ablated copper with time is plotted in figure 5. A total amount of 0.6 mg was obtained. Of course this quantity should increase with the current intensity value.

4. Conclusions

In this paper we presented a model in SF_6 plasma taking into account the ablation of a copper electrode. For the ablation process, two main cases must be distinguished: One corresponding to a diffusion process and another corresponding to a "convective" ablation. We detailed how to take into account the amount of copper linked with hydrodynamic equations. A transient case with a sinus half current wave at 10 kA was presented. This case shows the capacity of the model to describe the ablation process. Even if a small part of the electrode is ablated, the plasma totally burns in a copper medium without any SF_6 in its core. This means that in a real HVCB configuration, the fact to consider the copper ablation should change the properties of the plasma and then the models predictions. This effect will be more important increasing the current value.

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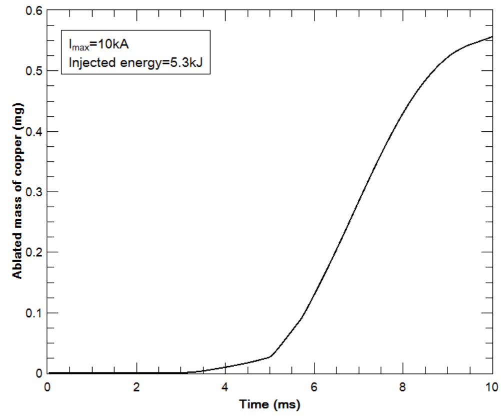

Figure 5. Ablation of copper material with time t.