A TWO DIMENSIONAL SIMULATION OF A NON EQUILIBRIUM DECAYING SF_6 ARC PLASMA

J.-B. Belhaouari, J.-J. Gonzalez, A. Gleizes

Centre de Physique des Plasmas et de leurs Applications de Toulouse
ESA n° 5002, Université Paul Sabatier, 118 route de Narbonne 31062 Toulouse cedex 4, France
Phone: +33-05-61-55-68-55 Fax: +33-05-61-55-63-32 e-mail: jjg@cpa11.ups-tlse.fr

ABSTRACT

We have developed a two dimensional model of decaying SF_6 arc, taking into account the departures from equilibrium due to chemical kinetics. The coupling between the hydrodynamic and the chemical equations is realized through the pressure and the mass density. In a first step we modelize the stationary state in order to obtain initial conditions of the transient study. We present the results obtained in the transient state showing the plasma cooling and the departure of the number densities from the equilibrium composition. The results lead us to observe a deviation from the equilibrium composition, with an overpopulation of S_2^+ density and an under-population of the electron on the edges of the plasma.

1. INTRODUCTION

During the arc extinction in H.V. circuit breakers there is a strong blowing leading to phenomena of turbulence. These mechanisms are responsible for the energy transfer necessary to the recovery of the dielectric rigidity. A modelling based only on thermal phenomena cannot explain the behaviour of the plasma where it exists chemical non-equilibrium resulting from turbulence or strong cooling (-10^8 $K.s^{-1}$). All the models based on the hypothesis of the local thermodynamic equilibrium (LTE) lead to a post-arc current, contrary to the experimental results where the post-arc current is often non-existent after the zero of the alternative current. To interpret this difference, we have to consider that molecular species may be present in the hot regions. So the plasma column should be cut by a portion of gas with a small electrical conductivity unlucky to the circulation of the electric current.

The general aim of this work is to simulate the decaying arc behaviour taking non equilibrium effects into account. So we have built a mathematical model coupling a hydrodynamic and kinetic study for an SF_6 gas in a two-dimension flow in a transient state. The coupling between hydrodynamics and kinetics is made through the pressure and the mass density.

2. SF_6 PLASMA COMPOSITION

The model is composed of the conservation equations of all the species, it is based on the following main assumption: i) the medium is homogeneous, ii) we assume a thermal equilibrium and the energy distribution functions of all species are Maxwellian, iii) the reaction rates are only functions of the mean temperature defined at time t, iv) there is no external forces, v) the pressure is constant and equal to 10^5 Pa.

We have considered 19 species: (e^-, S, S^-, S^+, S_2, S_2^+, F, F^-, F^+, F_2, F_2^+, SF, SF^-, SF^+, SF_4, SF_5, SF_6, SF_2, SF_3). 66 chemical reactions between these species are taken into account and are described in [1]. The direct reaction rates and the reverse rates are given in [2].

The conservation equation for species i is given by:

$$\frac{\partial n_i}{\partial t} + \vec{\nabla}\cdot\left(n_i \vec{V}\right) = Ca_i - n_i Da_i \qquad (1)$$

where n_i represents the particle density of specie 'i', Ca_i the number of particles created, $n_i Da_i$ the number of particles 'i' destroyed by unit of time and volume. The terms Ca_i and Da_i are functions of chemical reaction rates, calculated by Borge [1]. The pure SF_6 equilibrium composition is calculated by the equation (1) reduced to:

$$n_i = \frac{Ca_i}{Da_i} \qquad (2)$$

The model starts from an initial stationary state assumed be in LTE at high temperature (12000 K), and the temperature decreases down to 2100 K. The reaction rate equations (2) written for the stationary state are not linearly independent. Other relations exist to link the particle densities: the perfect gas law, electric neutrality and stochiometric equilibrium of SF_6.

The interest of this calculation is double, first of all it allows to obtain the equilibrium composition which may be used for analysing the results of the kinetic model, second, relaxation times (also called reaction time constants) can be estimated with the equilibrium composition and the reaction rate.

Figure 1 gives the obtained equilibrium variations of the particle densities versus the temperature at atmospheric pressure (10^5 Pa). Between 12000 K and 4500 K, the electrons constitute the prevailing of charged species.

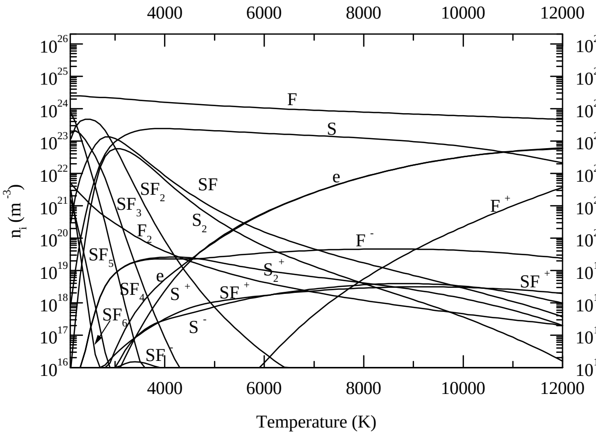

Figure 1: Variations of particle densities in equilibrium SF_6 plasma

3. KINETIC STUDY

In order to see if the electron number density can decrease by recombination, we have studied the relaxation time associated to the species. For a given mean velocity of particles 'i' we can define 'd' as the mean length that the species can make before being totally dissociated, by:

$$d = v' \tau^A \qquad (3)$$

The general from of the dissociation or recombination between atoms and molecules is given by relation (4), were K_d represents the direct rate and K_i the inverse rate. At equilibrium, the number of direct reactions is equal to the number of the inverse reactions by units of time and volume (5). Considering the equation:

$$A + B \underset{K_i}{\overset{K_d}{\rightleftarrows}} C + D \qquad (4) \qquad\qquad n_A n_B K_d = n_C n_D K_i \qquad (5)$$

For the reaction (4), the partiel relaxation time $\tau^A{}_p$ of species A is a function of the reaction rate K_d. The density n_B and is given by (6) and the total relaxation time of the species A for N reactions is (7).

$$\tau^A = \left(K_d n_B\right)^{-1} \qquad (6) \qquad\qquad \frac{1}{\tau^A} = \sum_{p=1}^{N} \frac{1}{\tau_p^A} \qquad (7)$$

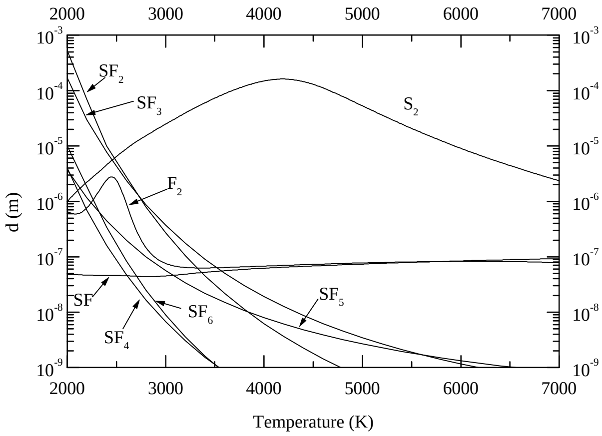

Figure 2: Mean path of molecules before dissociation in the plasma (v' = 10 m.s^{-1})

The mean length is presented in figure 2 versus the temperature for a velocity equal to 10 m.s^{-1} for molecular species SF_X (x=2,6) and diatomic species (S_2, SF, F_2). For the molecular species, an increase of the temperature leads to a decrease of 'd'. At 2500 K, the values of 'd' is between 10^{-8} m and 10^{-7} m, indicating a strong dissociation of these species. Figure 2 shows that SF_X (x=2,6) molecules have a weak probability to penetrate in regions where T > 3000 K, even if, in real circuit breakers the velocities are greater than the value considered here (10 m.s^{-1}). The distance 'd' for the diatomic species, more stable at high temperature, is greater than those of polyatomic molecules. There are two consequences of this result: First, the effect of convection on the electron density could exist through the diatomic molecules (S_2). Secondly, the polyatomic molecule densities should have values near the equilibrium composition. In figure 3 we have plotted the dominant relaxation time of the electron versus the temperature. The figure shows that the reaction of electron-ion recombinaison $S_2^+ + e \leftrightarrow S + S$ is responsible for the disappearance of electrons in temperature range 4000 K < T < 7000 K.

Two points can be brought out of the results: the effect of overpopulation of molecules S_2 gives an overpopulation of ions S_2^+ and this overpopulation of ion S_2^+ leads to an under-population of electrons.

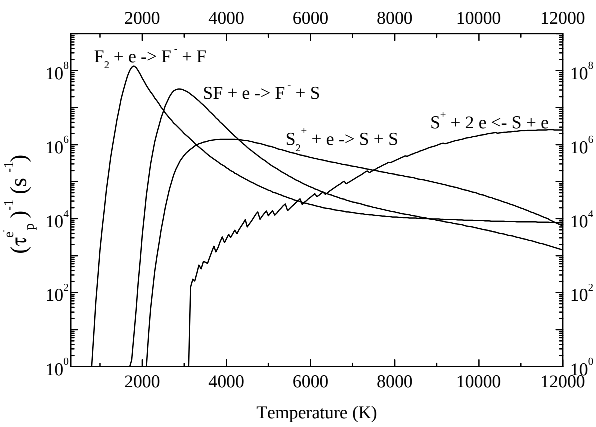

Figure 3: Contribution of the reactions on the total relaxation time of the electron

4. MATHEMATICAL MODEL

4.1. Hypothesis of the model

The model treats a two dimensional SF_6 arc in transient state. It is based on the following main assumptions: the plasma has a cylindrical symmetry; we consider that the transport coefficients: electrical conductivity σ, thermal conductivity K, specific heat C_P, viscosity μ [3], net emission coefficient ε_N [4] are only functions of temperature. For the net emission we assume an isothermal and homogeneous cylindrical plasma of radius Rp (Rp = 2 mm). Diffusion of particles is neglected. The calculation domain and boundary conditions are given in figure 4 and table 1. The dimensions of the calculation domain are respectively 2 cm and 0.5 cm on the axial and radial directions for a grid of 40 x 40 points. On the electrode (line EF) we made a preliminary study, resolving in a one dimension the equation (8) in order to give the boundary condition for the resolution of the 2D stationary model and to give the temperature and radial velocity components for the transient state.

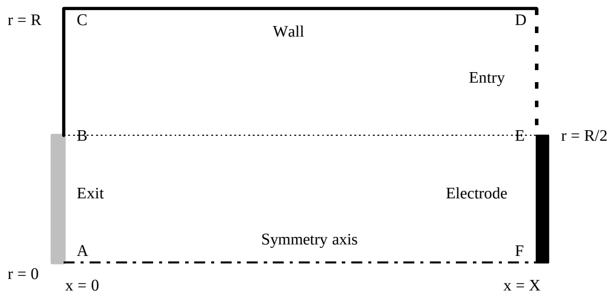

Figure 4: Calculation domain

	AB	BCD	DE	EF	FA
u	$\frac{\partial u}{\partial x}=0$	0	u (r,t)	0	$\frac{\partial u}{\partial r}=0$
v	0	0	0	Electrode model	0
T	$\frac{\partial T}{\partial x}=0$	3000 K	3000 K		$\frac{\partial T}{\partial r}=0$
n	$\frac{\partial n}{\partial x}=0$	$\frac{\partial n}{\partial r}=0$	n_{LTE}	n_{LTE}	$\frac{\partial n}{\partial r}=0$

Table 1: Boundary conditions

4.2. Equations of the stationary model

on the electrode (line EF)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,K\,\frac{\partial T}{\partial r}\right)+\sigma E^2-4\pi\varepsilon_N=0 \quad (8)$$

momentum $\vec{\nabla}\cdot\left(\rho\,\vec{V}\,\vec{V}\right)=-\vec{\nabla}P+\vec{\nabla}\cdot\left(\mu\,\vec{\nabla}\,\vec{V}\right)$ (9)

energy

$$\vec{\nabla}\cdot\left(\rho\,\vec{V}\,h\right)=\vec{\nabla}\cdot\left(\frac{K}{C_P}\nabla h\right)+\sigma E^2-4\pi\varepsilon_N+\vec{V}\cdot\vec{\nabla}P \quad (10)$$

where $\vec{V}$ is the velocity vector (u an v are the axial and the radial components of the velocity), P is the pressure, h the specific enthalpy. The resolution of these equations is based on the algorithms of Patankar [5].

4.3. Equations of the transient model

on the electrode (line EF)

$$\frac{\partial\rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v\right)=0 \quad (11)$$

$$\rho C_P\frac{\partial T}{\partial t}+\rho v C_P\frac{\partial T}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\,K\,\frac{\partial T}{\partial r}\right)-4\pi\varepsilon_N \quad (12)$$

species $\frac{\partial n_i}{\partial t}+\vec{\nabla}\cdot\left(n_i\,\vec{V}\right)=Ca_i-n_i\,Da_i$ (13)

momentum $\rho\frac{\partial\vec{V}}{\partial t}+\vec{\nabla}\cdot\left(\rho\vec{V}\vec{V}\right)=-\vec{\nabla}P+\vec{\nabla}\cdot\left(\mu\vec{\nabla}\vec{V}\right)$

(14)

energy

$$\rho \frac{\partial h}{\partial t} + \vec{\nabla}\cdot\left(\rho \vec{V} h\right) = \vec{\nabla}\cdot\left(\frac{K}{C_P}\nabla h\right) - 4\pi\varepsilon_N + \vec{V}\cdot\vec{\nabla} P \qquad (15)$$

Coupling $$P = \sum_i n_i\, k_b\, T \qquad \rho = \sum_i m_i\, n_i \qquad (16)$$

4.4. Calculation

In stationary state the calculation is made for current intensity I equal to 50 A and mass flow rate D_0 equal to 0.2 $g.s^{-1}$. The electric field E is constant and uniform. The gas entry is situated on the line DE where the axial velocity profile u(r) of the inlet flow is parabolic. In order to have a rather strong blowing during the extinction, we impose an increase of the inlet flow in transient state given by:

$$D = D_0\,(1+29\ t/2.10^{-5})\ g.s^{-1} \qquad (17)$$

After the current zero the electric field E = 0. The initial profiles of temperature, velocities and the 19 species densities are given by the stationary model. The time step, Δt is chosen using a chemical criterion: $\Delta t = \left[(Da)_{Max}\right]^{-1}$, where $(Da)_{Max}$ represents the maximum destruction rate of any species.

4.5. Results and discussion

The results are presented for a time equal to 20 µs. The temperature field is plotted in figure 5. We can note a pinching on the entrance due to the strong convection. In figure 6 we have plotted the relative electron density field (the relative density is defined as the ratio of the calculated density on the equilibrium value $n_{LTE}(T,P)$). Our results show mainly an under-population of electron density on the edges of the arc that means in the temperature range 4000 K < T < 6000 K. In figure 7 we have plotted the relative density of S_2^+. We can note an overpopulation of S_2^+ density on the edges of the arc, due to a strong overpopulation of S_2 molecules. The under-population of electron density is explained by the electron- S_2^+; this effect is strengthened by the convection of the cold gas.

These results on the influence of the convection, on chemical kinetics show that a strong convection or phenomena of turbulence can lead to an under-population of electron density in a critical temperature range for the post-arc phase.

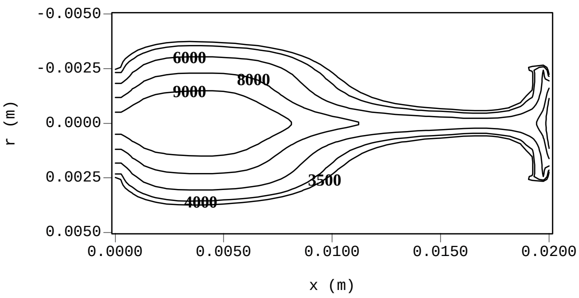

Figure 5: Plasma temperature field (K)

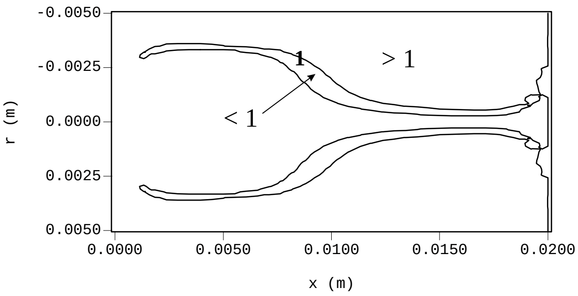

Figure 6: Relative density field (electron)

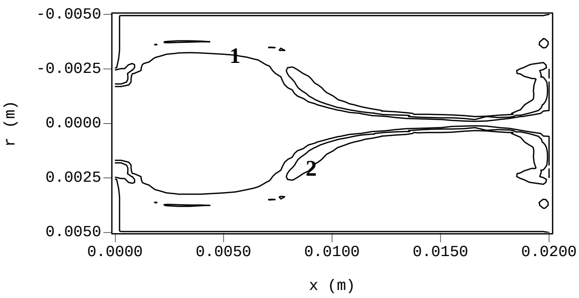

Figure 7: Relative density field (S_2^+)

ACKNOWLEDGMENTS

The authors thank Electricité de France and GEC Alsthom which partly financed the study.

REFERENCES

[1] Borge E., 1995, Doctorat de l’Université Paul Sabatier n° 2051.
[2] Gleizes A et al, 1991, J. Phys. D: Appl. Phys., **24**,1333-8.
[3] Chervy B., Gleizes A., Razafinimanana M., 1994, J. Phys. D: Appl. Phys., **27**, 1193.
[4] Gleizes A et al. 1993 , J. Phys. D: Appl. Phys., **26**,1921.
[5] Patankar S. V., 1980, ‘Numerical Heat Transfert and Fluid Flow’ Hemisphere Pub. Corp.