KINETIC STUDY OF A DECAYING SF_6 ARC PLASMA

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ABSTRACT

We have developed a one dimensional model of decaying SF_6 arc, taking into account the eventual departures from equilibrium due to chemical kinetics. The coupling between the hydrodynamic and the chemical equations has been realised through pressure and mass density. In a first step we have treated the stationnary state in order to obtain initial conditions of the transient study. The first part is devoted to the basis of the model. We present, then 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 on the equilibrium composition, with an overpopulation of the electrons on the axis and an underpopulation on the edges of the plasma. On the second part of the results, we present a special study on the mean distance that the species can made before being totally dissociated, allowing to interpret the results of the general model.

INTRODUCTION

The SF_6 gas is currently used in H.V. circuit breakers because it presents chemical properties giving a high interruption capability. During the extinction there is a strong arc blowing leading to phenomena of turbulence. These mecanisms are responsible for the energy transfer necessary to the recovery of the dielectrical rigidity. So a modelling based only on thermal phenomena cannot explain the behavior 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. In this first step of the study presented here we build a mathematical model coupling an hydrodynamic and kinetic study for an SF_6 gas in a one dimension in a transient state. This description is far from the difficult problem of a circuit breaker arc but allows us to adapt the cooling of the plasma or the convection velocities to differents configurations by increasing artificially the thermal conductivity by a constant factor. We obtain temperature profiles and the composition of the SF_6 plasma in a stationary and in the transient cases.

BASIS OF THE MODEL

The model treats a one dimensional wall-stabilized SF_6 arc in transient state. The axial flow of the gas and thus the axial component of its velocity are negligible. During the arc decay there is a radial convection and the pumping of the surrounding gas. The hypotheses concerning axial and radial convection have been analysed and justified theoretically and experimentally in a wall-stabilized arc burning in argon by Gleizes et al [1].

The model is based on the following main assumptions: the plasma has a cylindrical symmetry; the electric field E is constant and uniform; we consider that the transport coefficients (electrical conductivity σ [2], thermal conductivity κ [2], net emission coefficient ε_N) are only functions of temperature and pressure. The net emission coefficient has been calculated using the method given in [3], assuming an isothermal and homogeneous cylindrical plasma of radius Rp (Rp = 2 mm). The wall temperature is T_W=3000 K and $(\partial T/\partial r)_{r=0} = 0$ on the axis. The arc diameter is 5mm and the initial current intensity 50A. This intensity leads to temperatures in the range 12000-3000 K including 23 species (e^-, S, S^-, S^+, S_2, S_2^+, F, F^-, F^+, F_2, F_2^-, F_2^+, SF, SF^-, SF^+, SF_4, SF_4^-,SF_5, SF_5^-, SF_6, SF_6^-, SF_2, SF_3). During the arc decay, the axial flow of the gas and thus the axial component of its velocity are negligible in comparison with the radial convection, the unknowns are the temperature T(r,t), the radial velocity V_r(r,t), and the N species densities n_i(r,t). Diffusion of particules is neglected. The resolution is based on the algorithms of Patankar [5].

energy conservation

$$\rho\, C_P \frac{\partial T}{\partial t} + \rho\, C_P\, V_r \frac{\partial T}{\partial r} = \sigma E^2 - 4\pi\varepsilon_N + \frac{1}{r}\frac{\partial}{\partial r}\left(r\,\kappa \frac{\partial T}{\partial r}\right) \tag{1}$$

C_p and κ are respectively the specific heat and the thermal conductivity.

radial momentum

$$\rho \frac{\partial V_r}{\partial t} + \rho\, V_r \frac{\partial V_r}{\partial r} = \frac{2}{r}\frac{\partial}{\partial r}\left(\mu\, V_r\, r \frac{\partial V_r}{\partial r}\right) - \frac{\partial P}{\partial r} - \frac{2\mu V_r}{r^2} \tag{2}$$

μ is the viscosity

ohm's law

$$E = E_Z = \frac{I}{G} \qquad G = 2\pi \int_0^R \sigma\, r\, dr \tag{3}$$

where G is the conductance

species conservation

$$\frac{\partial n_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\, n_i\, V_r \right) = Ca - n_i\, Da \tag{4}$$

Dalton's equation

$$P = \sum_i n_i\, k_b\, T \tag{5}$$

mass density

$$\rho = \sum_i m_i\, n_i \tag{6}$$

n_i represents the particle density of specie 'i', Ca the number of particle created, n_i Da the number of particle 'i' destroyed by unit of time and volume. The terms Ca and Da are functions of chemical reaction rates, calculated by Borge [4]. The models (hydrodynamic and chemical) are coupled with the mass density (6) and the pressure (5). The time step, Δt is chosen using a chemical criterion:

$$\Delta t = \frac{1}{(Da)_{Max}} \tag{7}$$

Were $(Da)_{Max}$ represents the maximum number of any particle destroyed.

Stationnary state:

Before the arc decay the temperature profile in stationary state is given by the Elenbaas Heller equation. The first member of the equation (2) is zero. The initial densities are given by the equation (5) resuming to: $n_i = \frac{Ca}{Da}$

In equilibrium, the term of creation is equal to the term of loss. Figure 1 shows the 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 majority of charged species. The minority species F_2^-, SF_4^-, SF_5^-, and SF_6^- will not be taken into account in the transient state.

Arc decay:

After the current zero the electric field E=0. The fall of the pressure created by the cooling of the plasma and the resulting recombinaisons is compensated by a pumping of the surrounding gas so by a radial velocity.

RESULTS

Part one:

The results are presented for an arc of 2.5 mm radius and 300 radial points. We have plotted in figure 2 the transient evolutions of the temperature profiles. The axial temperature is equal to 10903 K and the electric field is 1193 $V.m^{-1}$ for an initial current of 50 A. At the extinction we obtain a plasma cooling rate of about -4. 10^7 $K.s^{-1}$ on the axis. This value is lower than the experimental [6] one (about -10^8 $K.s^{-1}$). This difference can been explained by the presence of peaks on the thermal conductivity centered around 1800 K and 2200 K and which are not taken into account choosing a wall temperature equal to 3000 K. In figure 3 we have plotted the radial profiles of the relative ionised species densities at t = 100 μs (the relative density is defined as the ratio of the calculated density on the equilibrium value). Our results show mainly an overpopulation of the electron density in the central arc, but an underpopulation of electron density has been obtained near the wall. This phenomenon is explained by the electron attachement on the molecules, this effect is strengthened by the convection of the cold gas.

Second part:

In order to see if this overpopulation of the electron number density can decrease by recombination, we have studied the relaxation time associated to the species. For a given velocity of the particle 'i' we can define 'd' (12) as the mean length that the species can made before being totally dissociated. The general chemical reaction of the dissociation or recombination between atoms and molecules is given by relation (8), were K_d represents the direct rate and K_i the inverse rate. At equilibrium, the number of direct reactions (velocity of the reaction) is equal to the number of the inverse reactions by unit of time and volume (9).

Considering the equation:

$$A + B \underset{K_i}{\overset{K_d}{\rightleftarrows}} C + D \qquad (8) \qquad\qquad n_A n_B K_d = n_C n_D K_i \qquad (9)$$

The relaxation time τ^A of species A is a function of the reaction rate K_d and of the density n_B and is given by: $\tau^A = \left(K_d n_B\right)^{-1}$ (10)

and the total relaxation time of the species A for the N reactions is $\frac{1}{\tau^A} = \sum_{p=1}^{N} \frac{1}{\tau_p^A}$ (11)

$$d = v\,\tau^A \qquad (12)$$

This mean length is presented in figure 4 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 an increase of 'd'. At 2500 K, the values of 'd' lay between 10^{-8} m and 10^{-7} m, imdicating a strong dissociation of these species. The calcul of equilibrium composition shows that the electrons play a role in the electrical conductivity only when T > 3000 K. Figure 4 shows that SF_X (x=2,6) molecules have a weak probability to penetrate in this region, even if, in real circuit breakers the velocities are greater than the value considered here (10 $m.s^{-1}$). On the other hand, 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. Secondly, the polyatomic molecule densities should have values near the equilibrium composition.

FIGURES

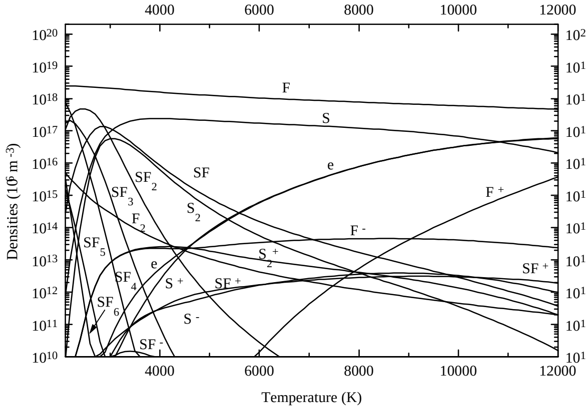

Figure 1: Variations of some equilibrium densities in equilibrium SF_6 plasma

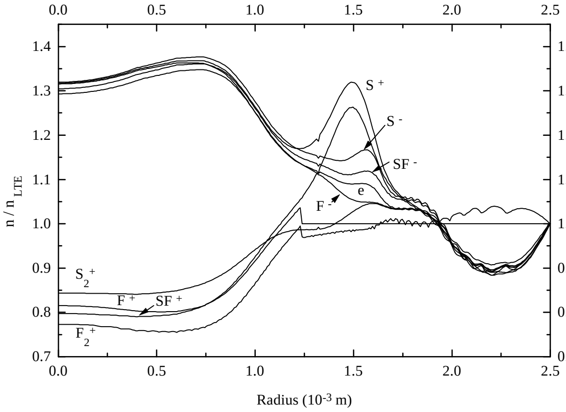

Figure 3: Variations of relative normalized densities (t = 100 µs)

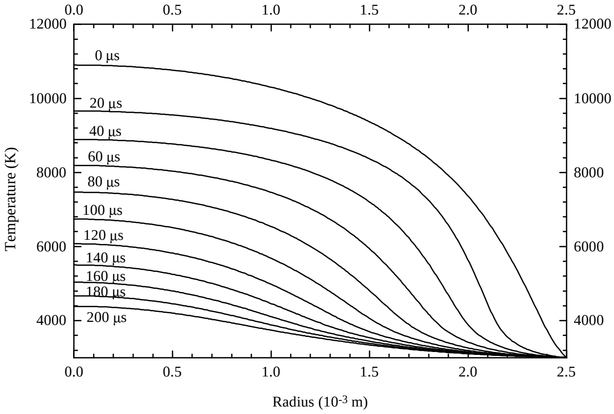

Figure 2: Evolutions of temperature profiles during the arc decay

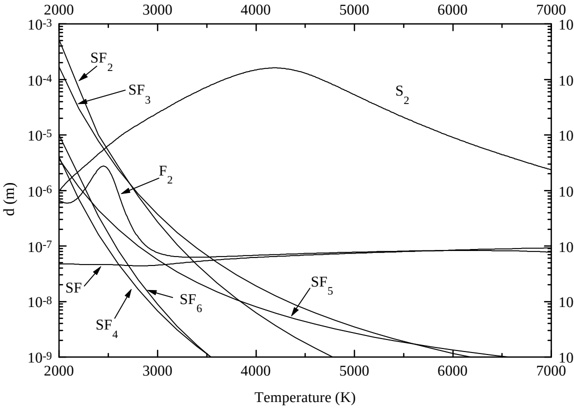

Figure 4: Mean path of molecules before dissociation in the plasma

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