TWO-DIMENSION HYDRODYNAMIC MODEL AND KINETIC MODEL OF A DECAYING SF6 ARC PLASMA

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INTRODUCTION

During the decay of a circuit-breaker arc, the plasma is subjected to strong blowing which can lead to deviations from chemical equilibrium. The intense convection may therefore be responsible for the presence of cold gas in the hot parts of the plasma. The cold particles then rapidly recombine with electrons, modifying the resistivity of the plasma. All the models based on the hypothesis of LTE lead to a post-arc current, unlike in experimental results where post-arc current is often non-existent after the zero of the alternating current. To interpret this difference, we have to consider that molecular species may be present in the hot regions. So, the plasma column could be cut by a portion of gas with low electrical conductivity hindering the circulation of electric current. So a model based only on thermal phenomena cannot explain the behaviour of the plasma where chemical non-equilibrium exists as a result of turbulence or strong cooling (-10^8 $K.s^{-1}$). In order to study this phenomenon as it appears in circuit-breakers, we modelled the extinction of an SF_6 arc for a simplified geometry. The 2-dimensional model that was set up was furthered by a study of the kinetics of SF_6 which enabled us to identify the various reaction processes governing the disappearance of electrons.

SF_6 PLASMA COMPOSITION

The assumptions made to calculate the composition with the kinetics model are the following: the medium is homogeneous and in thermal equilibrium; the energy distribution functions of all species are Maxwellian; the reaction rates are solely determined by the mean temperature; there are no external forces; the pressure is constant. The results presented here are for $P = 10^5$ Pa. For temperatures between 2100 K and 12000 K, we 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). In order to avoid excessive calculation times, the minor species, such as (SF_5^+, SF_4^+, SF_3^+, SF_2^+, F^{2+}, S^{2+}...) were ignored. Similarly, the negative ions (F_2^-, S_2^-, SF_6^-, SF_5^- and SF_4^-), which were present in very small amounts over the temperature range considered (2100 K < T < 12000 K) were not taken into account. A preliminary study of the reactions showed that these species are only weakly involved in electron capture processes. Sixty-six chemical reactions were taken into account and have been described in [1]. Most of the direct reaction rates proceed from reference [2], whereas the reverse rates were computed by micro-reversibility requiring the calculation of the partition functions. The conservation equation for species i is given by (1):

$$\frac{\partial n_i}{\partial t} + \vec{\nabla}\cdot\left(n_i\ \vec{V}\right) = Ca_i - n_i\ Da_i \qquad (1) \qquad\qquad n_i = \frac{Ca_i}{Da_i} \qquad (2)$$

The terms Ca_i and Da_i describe the chemical reaction rates and were calculated previously [1, 3]. In equilibrium conditions, the creation term is equal to the loss term and the SF_6 plasma composition is calculated by equation (1) which comes down to equation (2). The model is composed of 19 reaction rate equations. In fact these equations (2), written for the stationary state, are not linearly independent. Other relations exist to link the particle densities: the perfect gas law, electrical neutrality and stoichiometric equilibrium between S and F in the plasma. We thus obtained a table of plasma densities for temperatures between 12000 K and 2100 K with a step of 50 K.

HYDROKINETIC MODEL

The model deals with a 2-D SF_6 arc in the transient state and limited by a cylindrical wall. It is based on the following main assumptions: the plasma has a cylindrical symmetry and is in thermal equilibrium. We consider that the transport coefficients (electrical conductivity σ, thermal conductivity κ, specific heat C_P, viscosity μ [4], net emission coefficient ε_N [5]) are only dependent on temperature and pressure. The net emission coefficient has been used, assuming a mean plasma radius of 2 mm. Diffusion of particles is ignored. The calculation domain and boundary conditions are given in figure 1 and table 1.

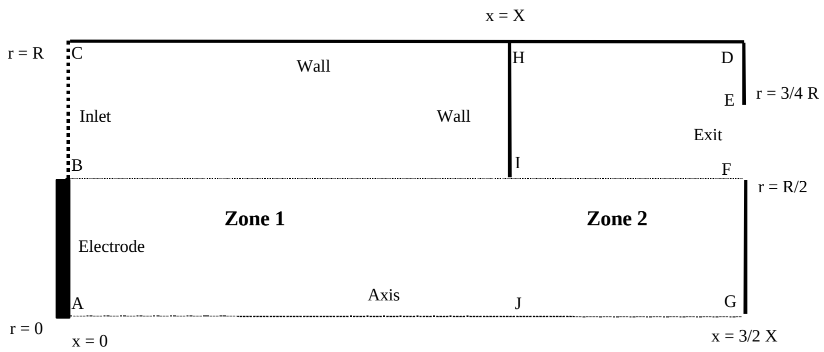

Figure1 : Calculation Domain

	AB	BC	CD	DE	EF	FG	GA	HI
u	0	u (r,t)	0	0	$\frac{\partial u}{\partial x} = 0$	0	$\frac{\partial u}{\partial x} = 0$	0
v	v(1D)	0	0	0	0	0	0	0
T	T(1D)	3000 K	3000 K	3000 K	$\frac{\partial T}{\partial x} = 0$	3000 K	$\frac{\partial T}{\partial x} = 0$	3000 K
n	n_{ETL}	n_{ETL}	$\frac{\partial n}{\partial r} = 0$	n_{ETL}	n_{ETL}	n_{ETL}	$\frac{\partial n}{\partial r} = 0$	n_{ETL}
p	p_0	p_0	$\frac{\partial p}{\partial r} = 0$	p_0	p_0	p_0	$\frac{\partial p}{\partial r} = 0$	p_0

Table1: Boundary conditions

The dimensions of the calculation domain are 3 cm and 0.5 cm in the axial and radial directions respectively for a grid of 60 x 40 points. The temperature at the wall (line BCD) is equal to 3000 K. In stationary state, the gas entry is situated on line BC where the axial velocity profile u(r) of the inlet flow is assumed to be parabolic. The mass flow rate D_0 is equal to 0.2 $g.s^{-1}$. In order to limit the axis temperature in the stationary state (the reaction rates were computed for $T \leq 12000$ K) and to have rather strong blowing during extinction, we imposed an increasing inlet flow in the transient state during the first 20 μs.

$$D(t) = D_0 \left(1 + \frac{29\,t}{2.10^{-5}} \right) \qquad (0 < t < 2.\ 10^{-5}\ s) \qquad (3) \qquad D(t) = 30\ D_0 \quad (t > 2.\ 10^{-5}\ s) \qquad (4)$$

The resolution of the equations is based on the algorithms of Patankar [6]. The boundaries conditions on the pressure are directly deduced on the densities conditions, so we have at the entry

(BC) an inlet given pressure P = 0.1 MPa and Neumann conditions on the walls. The parameters to be calculated (temperature, velocity and pressure) depend on the local variables r (radial distance) and x (axial distance). Classical Navier Stockes equations are used for the resolution [7]. In the transient state we also calculate the species densities ; all the unknowns are then dependent on the three variables (space and time). The models (hydrodynamic and kinetic) are linked through pressure (5) and mass density (6).

$$P = \sum_i n_i \, k_b \, T \qquad (5) \qquad\qquad \rho = \sum_i m_i \; n_i \qquad (6)$$

RESULTS

During extinction, from t = 0, the electric field is taken as being nil. The initial profiles of temperature and velocity are given by the stationary model and the initial densities of the 19 species are given by the equilibrium composition. The time step Δt is set at 10^{-10} s, this value is chosen using a kinetic criterion: $\Delta t = \left[(\mathrm{Da})_{\mathrm{Max}}\right]^{-1}$, were $(\mathrm{Da})_{\mathrm{Max}}$ represents the maximum value of Da_i. For the calculation of time Δt, the densities of the molecular SF_X (X = 2 to 6) species are not taken into account. We present results of the hydrokinetic model during arc decay for an initial pressure and current intensity equal respectively to one atmosphere and 50 A. Figure 2 presents the temperature field (in Kelvin) during decay for times of 20μs. A constriction occurs on the temperature profiles near the upstream electrode. On extinction there is an increase of the radial velocities towards the axis of the arc because of pumping phenomena which tend to compensate for the drop in pressure caused by cooling. We then see the steady inclusion of the cold injection gas which disturbs the plasma by cooling it. At 20 μs, the Mach number is close to 1 everywhere with maximum values of 1.4 on the input layer (line DE).

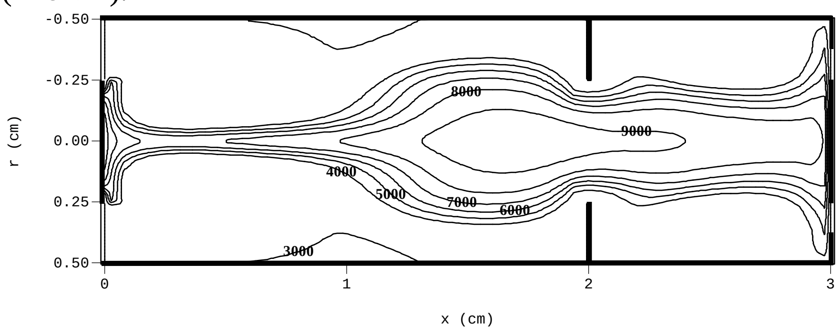

Figure 2 : Temperature field t=20μs

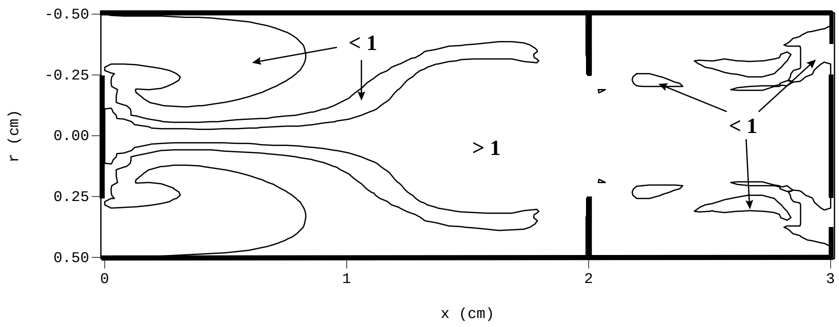

Figure 3 : Electron number density t=20μs

In figure 3 we have plotted the relative electron number density field (the relative density is defined as the ratio of the calculated number density to the equilibrium value of the local pressure and temperature). Our results mainly show an under-population of electron density at the edges of the plasma *i.e.* in the temperature range 4000 K < T < 6000 K.

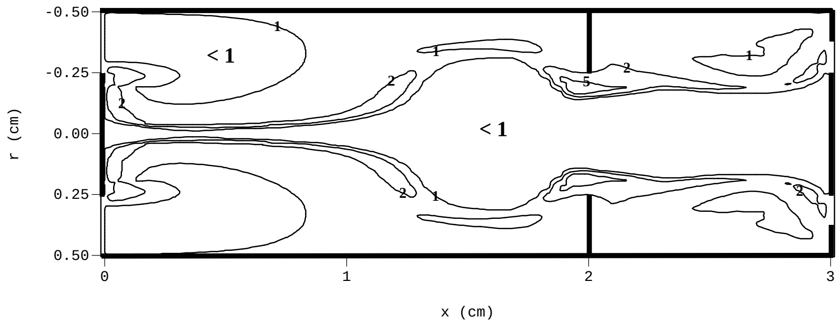

Figure 4: S_2^+ number density t=20µs

In figure 4 we have plotted the relative densities of S_2^+. We can note an overpopulation of S_2^+ at the edges of the arc. The under-population of electron density is explained by electron recombination with S_2^+ molecules, this effect being enhanced by cold gas convection. In fact, it is difficult to compare the results obtained with two different values of the inlet mass flow rate. For a given time, the temperature fields are not identical, but a comparison made between two different times leading to approximately the same temperature field shows that the electron under-population is accentuated by the convection. The results show that departures from equilibrium created by strong convection can lead to an increase of the plasma resistivity. They show a disappearance of the electron density more quickly than we can deduced from an equilibrium composition on a temperature range 4000-6000K. But as we can found using equilibrium model, it is a critical temperature range for thermal cut-off in SF_6 circuit breakers.

CONCLUSION

The hydrodynamic model, using simplified geometry, predicts the occurrence of electron under-population in regions where the temperature is between 4000 and 6000 K, a critical temperature range for thermal cut-off in SF_6 circuit breakers. The study has shown that the disappearance of electrons can be explained by electron-ion recombination with S_2^+ molecules and that this effect is enhanced by cold gas convection.

This paper is the first step in the study of deviations from equilibrium in models of decaying circuit-breaker arcs. Now, we are developing a two-temperature model that may include deviations from thermal equilibrium occurring when a recovery voltage is applied to the decaying arc plasma.

ACKNOWLEDGMENTS

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