TWO-TEMPERATURE STUDY OF A DECAYING SF_6 ARC PLASMA

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INTRODUCTION

This paper is the second step in the study of deviations from equilibrium in models of decaying circuit-breakers arcs. The first step was based on a kinetic approach which allowed us to study the influence of deviations from the chemical equilibrium.

During the decay of a circuit-breaker arc, and immediately after current zero, a recovery voltage appears that tends to warm residual electrons, which can lead to the reignition of the arc. If the energy transfer between electrons and heavy particles is not enough effective, the electron temperature in the medium is rapidly higher than the heavy particle temperature. Thus, there is a departure from the thermal equilibrium. In order to study this phenomenon and its influence on the success or the failure of circuit-breaking, we developed one-dimension transient model of an SF_6 arc for a simplified geometry which enabled us to show its impact on several parameters.

Electron and heavy particle temperatures are mainly coupled through an energy exchange term which appears in the energy equations. We showed [1] its dependence on the plasma composition, leading to the micro-reversibility law used to determine this composition. In this paper, we study the arc itself and how thermal non-equilibrium acts on temperature and velocity profiles, and on parameters such as electrical conductivity.

HYPOTHESES

The aim of this study is not to simulate very precisely the behavior of a circuit-breaker and all the phases of the arc decay, but to show the influence of thermal departures from equilibrium on the arc characteristics in order to explain the differences between the results of experience and those of more complex models based on the hypothesis of local thermodynamic equilibrium. Therefore, the first step is to develop one-dimension two-temperature SF_6 arc model at extinction. This model implies the computation of the composition, transport coefficients and thermodynamic properties for the two-temperature plasma.

We suppose cylindrical symmetry. The fluid is characterized by a laminar flow; conduction, radiation losses and energy exchange through elastic collisions between electrons and heavy particles are taken into account, axial convection is supposed negligible. The pressure remains constant in the discharge. The transport coefficients are only functions of the temperature, of $\theta = T_e/T_h$ (electronic temperature by heavy particle one) and of the pressure. The electric field is supposed to be equal to zero in transient state. For two temperature transport coefficients we use values calculated in our team [2].

A two temperature model means that the energy transfer between electrons and heavy particles is not enough efficient to consider the plasma in thermal equilibrium. Hence, there are two energy distributions leading to two temperatures: electron temperature T_e and heavy particle temperature T_h. We thus obtain one energy equation for electrons (2) and one for heavy particles (3).

EQUATIONS

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\rho\,V_r\right)=0 \tag{1}$$

$$\rho_e\,C_{Pe}\,\frac{\partial T_e}{\partial t}+\rho_e\,C_{Pe}\,V_r\,\frac{\partial T_e}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\kappa_e\,\frac{\partial T_e}{\partial r}\right)-U-E_{eh} \tag{2}$$

$$\rho\,C_P\,\frac{\partial T_h}{\partial t}+\rho\,C_P\,V_r\,\frac{\partial T_h}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\kappa_{eff}\,\frac{\partial T_h}{\partial r}\right)+E_{eh} \tag{3}$$

$$E=E_z=\frac{I}{G} \tag{4}$$

$$G=2\pi\int_0^R \sigma\,r\,dr \tag{5}$$

To initialize the calculation in stationary state, eq. (2) and (3) are reduced to their right part. In eq. (2) we successively identify in its right part the thermal conduction term, Joule's effect, radiation losses, and a forth term: E_{eh}. It is this term which realizes the coupling between electron temperature T_e and heavy particles' one T_h. It represents energy exchange through elastic collisions between electrons and heavy particles. Inelastic collisions are involved in energy transfer through the radiation losses term and implicitly through the reaction thermal conductivity. The mass conservation equation (1) completes our system of equations.

BOUNDARY CONDITIONS

We chose the following boundary conditions :

- On the axis :

$$\left(\frac{\partial T_e}{\partial r}\right)_{r=0}=0 \qquad \left(\frac{\partial T_h}{\partial r}\right)_{r=0}=0 \qquad \left(V_r\right)_{r=0}=0$$

- At the wall (domain limit) :

$$\left(\frac{\partial T_e}{\partial r}\right)_{r=R}=0 \qquad T_h(R)=3000\text{K} \qquad \left(\frac{\partial\, r\,\rho\,V_r}{\partial r}\right)_{r=R}=0$$

RESULTS

We present here the results obtained for a curent intensity of 50 A, for a pressure of 1 atm, and for a plasma radius of 2.5 mm. The grid has 300 points (radialy). During the decay, the time step is fixed to 0.1µs. We studied the influence of the grid and of the time step on the computation, our values correspond to the best compromise between precision and computation time.

Fig. 1 and 2 represent respectively the evolution during the decay of T_h and T_e profiles. Either for heavy particles or for electrons we obtain a cooling speed on the axis of about 2.5 to 3 10^7 Ks^{-1}. This value could seem low regarding to the one given by equilibrium models [3] which is of about 10^8 Ks^{-1}. There are two ways to explain it : first of all the boundary condition of 3000 K at the wall do not allow us to take into account the peaks of reaction thermal conductivity, which are included in effective thermal conductivity; secondly the fact that we have a temperature departure between electrons and heavy particles means that some energy is trapped by the electrons, and is then restitute to the heavy particles during the decay, thus slowing down the cooling.

Fig. 3 shows the evolution of temperature departure (T_e - T_h) during the decay. This departure between T_e and T_h decreases near the wall while it increases in the inner part of the arc. During the first twenty microseconds there is, in the center of the discharge, a thermalisation of the energy (T_e tends to T_h). Our results show that a departure appears after this thermalisation phase.

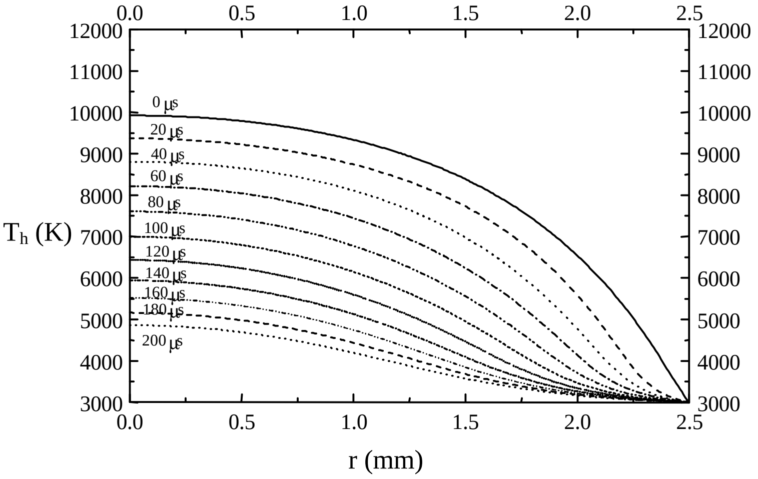

Figure 1 : Heavy particles temperature profile during the decay.

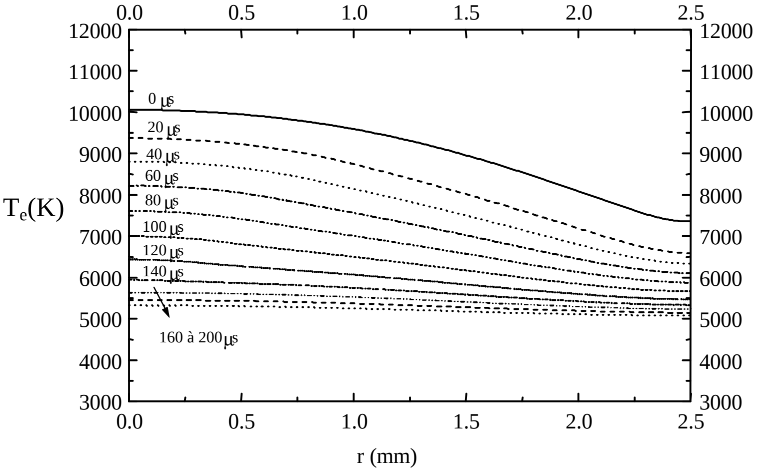

Figure 2 : Electronic temperature profile during the decay.

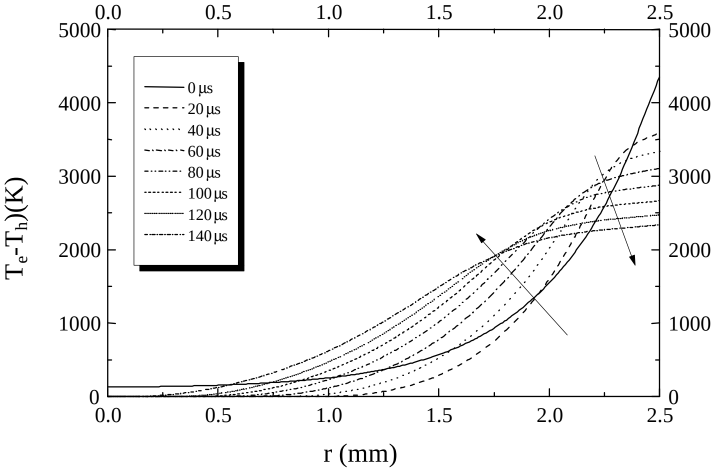

Figure 3 : Evolution of temperature departure (T_e-T_h) during the decay.

Fig. 4 shows the evolution of radial velocity profile with time. The radial velocity is generated by the gas pumping during the decay, thus this velocity is initially equal to zero. We then obtain a centripetal velocity which maximum decreases with time. At 20 µs this maximum has a value of $V_r = -4$ m/s. This value can be compare to that of an equilibrium model which is of –6 m/s at 20 µs. As the plasma cooling is slower in our two temperature model, the pumping of exterior gas is lower.

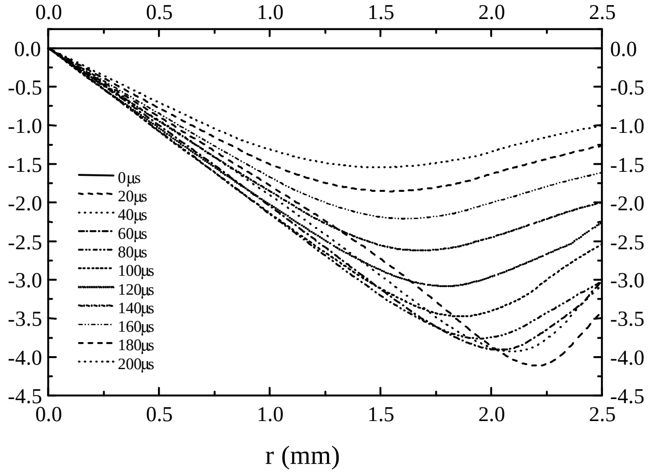

Figure 4 : Evolution of radial velocity profile during the decay.

CONCLUSION

The aim of this paper was to define the theoretical bases on a SF_6 arc model, taking departure from thermal equilibrium into account. As regards to an equilibrium model we founded a slower cooling. Some energy is trapped into the reservoir constituted by the electrons, and is then restituted to the heavy particles during the decay, slowing down the cooling. Moreover, effective thermal conductivity decreases when θ grows, at low electron temperature. Thus, energy loses due to thermal conduction are lower.

Our results show that taking thermal departures from equilibrium into account leads to a lower interrupting capability, which was not expected. We are developing a two temperature model in order to solve two-dimension problems, with the aim to couple it with an hydro kinetic model. We will be able then to show the influence of both thermal and chemical departures from equilibrium on the electrical conductivity and on the conductance.

ACKNOWLEDGEMENTS

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