Numerical Investigations of the Cathode Region of Electric Arcs

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Abstract: A modeling approach is presented for the description of the structure of the cathode region of an electric arc and its influence on the whole discharge. A systematic numerical study of the influence of the voltage drop in the space charge zone is reported in this paper.

Introduction

Despite intensive investigations in the subject of arc cathode region phenomena, both experimental and theoretical, during the passed years, still there are some fundamental questions without answer in this field, see e.g. [1] and [10]. This situation is due to the fact that the processes near the cathode are very complicated, highly non-linear and coupled in a very complex manner. Many theoretical models, e.g. see [4] and [9], have been formulated to predict the cathodic spot conditions. Usually, these models need several assumptions.

Recently, a method for the thermal and electrical coupling between the arc column and the condensed phase of the cathode have been developed in our laboratory [7]. In this frame, a model for the cathode sheath has been developed. The model is based on a non equilibrium description of the transition layer between the arc column plasma where Local Thermodynamical Equilibrium (LTE) is assumed and the condensed phase of the cathode. The space charge zone in contact of the cathode is included in our model. This zone allows to derive the appropriate boundary conditions on the cathode wall for the computation of the electronic density and the temperature of electrons and heavy particles in the ionization zone. Therefore, it connects the ionization layer to the cathode.

In this paper, results from one-dimensional computations of the cathode region and from two-dimensional thermal and electrical coupling between the arc and the cathode are presented in terms of the voltage drop in the space charge sheath.
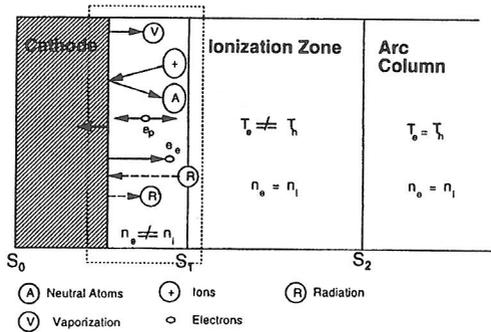
Cathode region Model

Figure 1: One dimensional picture of the cathode region

Experimental investigations and numerical simulations of high pressure arcs have shown that the temperature in the arc column is maximum near the cathode. Therefore, a high gradient of temperature seems to be present in the cathode layer as the temperature in the cathode is relatively low. One consequence of the low temperature just close to the cathode wall is that, at (LTE), thermal energy of particles is not sufficient for ionization of argon atoms. Therefore, other effects have to be present to complete the current transfer in this layer. In the present work, a non-equilibrium plasma model for the cathode region is used see [3]. The model contains integration of six coupled equations: equation of conservation of electron density, which accounts for ionization and recombination, equation of state, generalized Ohm's law, conservation of the current density and two separate electron and heavy particles energy balance equations. The last two equations consider the elastic and inelastic collisions in the plasma. However, boundary conditions on the cathode surface are of crucial importance for this model. In order to derive these boundary conditions, it is assumed that a Space Charge Zone (SCZ) is formed beween the ionization zone and the cathode. It is noteworthy that this assumption is usually used in litterature [6], [2]. Figure 1 gives a picture of the cathode region adopted in this work.

Due to the thickness of the (SCZ), which is of the order of the Debye length, collisions for momentum exchange are assumed to be negligible in this layer. A direct consequence of this assumption, is that particles fluxes are conserved in the (SCZ). Three kinds of current densities are considered in this zone: ion current density (J_i), back-diffusion electron current density (J_e^d) and the emitted electron current density (J_e^e).

For the numerical resolution of the equation of the conservation of electron number density in the ionization zone, the total electron current density ($J_e = J_e^e + J_e^d$) in the (SCZ) is set as a boundary condition at (S_1) for this equation. From an analytical solution to the Boltzmann equation in the (SCZ), see [8], the back-

diffusion electron current density has been connected to the emitted electron current density, to the number density of ions at the top of the (SCZ), to the electronic temperature (T_e^1) at (S_1) and to the cathodic fall (φ_c).

In this paper two cases are considered: first (case 1), the ion current density is calculated by assuming a Maxwell-Boltzmann distribution function for ions at (S_1). In this case, the ion current density is a function of the number density and the temperature of ions (T_w) at this boundary limit. Therefore, the electron current density J_e, can be deduced from the total current density J_T by $(J_e = J_T - J_i)$. In the second case (case 2), an assumption on the emission mechanism is made. In this case, the emitted electron current density is given and therefore, the total electron current density can be calculated directly. In this work, the thermionic emission mechanism is chosen.

The energy flux balance at the cathode wall is also very important in an arc discharges and requires a particular attention. According to our unified treatment of the cathode together with the cathode sheath, the states of particles inside the metal and at the top of the (SCZ) (S_1) are known. First, from the free electrons energy flux balance at (S_1), the following relation is found:

$$\lambda_e \frac{\partial T_e}{\partial z} = -J_e^e \frac{2.5k}{e}(T_e^1 - T_w) + J_e \varphi_c \tag{1}$$

The left hand side of the above equation is the thermal flux of electrons in the ionization zone at (S_1). The first term of the right hand side represents the thermalisation of the emitted electrons at (S_1) and the second one corresponds to the acceleration of electrons in the (SCZ). Finally, from the global energy flux balance over the (SCZ), and using equation (1), the conduction flux into the cathode is deduced by:

$$\lambda_s \frac{\partial T_s}{\partial z} = \lambda_h \frac{\partial T_h}{\partial z} - J_i \left(2.5 \frac{kT_w}{e} - \phi_{eff} + \varphi_c + E_i \right) - q_s \Delta h_l$$

$$+ J_e^d \left(\frac{2.5k}{e}(T_e^1 - T_w) + \phi_{eff} \right) + J_e^e \phi_{eff}, \tag{2}$$

where, q_s, Δh_l, ϕ_{eff} and E_i are the metal vapor mass flux, the latente heat of vaporization, the effective work function of the cathode material and the ionization energy of argon atoms. The above equation traduces the fact that, the cathode is heated by thermal flux of heavy particles in the ionization zone, by ions and by back-diffusion electrons. And it is cooled by thermal conduction in the metal, by vaporization and by electron emission. The term $J_i E_i$ appears in equation (2) because it is assumed that all ions recombine on the cathode wall and come back to the plasma as neutral atoms.

Results and discussion

In order to make detailed investigations of the arc-cathode region behavior, the problem studied first, is that of figure 1, where, only the cathode, the (SCZ) and the ionization layer are considered. In this part, the three regions cited above are assumed to be one-dimensional. To solve the energy equation in the cathode together with the second-order equations of the ionization zone, the temperature (T_w^0) in the metal at (S_0), the common temperature (T) of electrons and heavy particles at (S_2) and the current density (J_T) at (S_2) are required. These variables are fixed, according to experimental observations, to the following values: $(T_w^0 = 1000\ K,\ J_T = 10^8\ A/m^2,\ T_h^2 = T_e^2 = T = 21000\ K)$
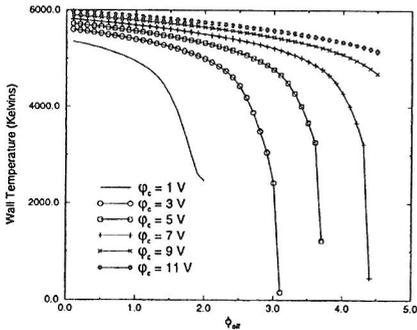

Figure 2: Wall temperature as a function of the cathodic fall and the effective work function (case 1)
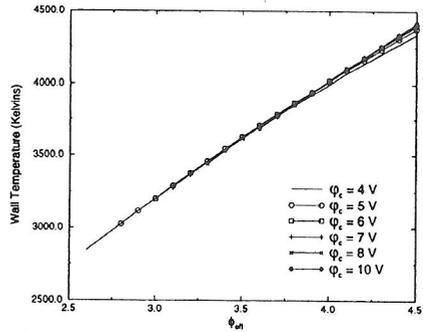

Figure 3: Wall temperature as a function of the cathodic fall and the effective work function (case 2)

Figures 2 and 3 show the temperature of the cathode wall as a function of the effective work function and the cathodic fall, corresponding to case 1 and case 2 respectively. In the first case, the wall temperature increases with the cathodic fall and decreases with the effective work function. The increase of the temperature with the cathodic fall is due to the increase of the energy flux transported by ions to the wall, while, the decrease of the wall temperature with the effective work function is mainly due to the cooling by electron emission. In the second case, one can notice that the influence of the cathodic fall on the wall temperature is negligible and that the temperature of the wall increases with the effective work function. The latter result is a direct consequence of the fast decrease of the emitted electron current density with the effective work function. This behavior leads to an increase of the ionic current density and therefore, the ion energy flux to the cathode. If one superposes figures 2 and 3, the couples (ϕ_{eff}, φ_c) consistent with both case 1 and case 2 can be deduced graphically.

A question which arises here, is how the choice of the cathodic fall can influence the behavior of the ionization layer. In order to investigate this issue, the effective work function has been fixed to $(3\ V)$ and calculations have been carried out for different values of the cathodic fall. Figure 4 illustrates the variation of

the temperatures of electrons and heavy particles for $(\varphi_c = 4V)$, $(\varphi_c = 7V)$ and $(\varphi_c = 10V)$. This results corresponds to case 1. It is worth mentioning that similar behavior has been obtained in case 2. This figure shows that the gap between electrons and heavy species temperatures increases with the cathodic fall. This entails a growth of the electronic density near the cathode wall and therefore influences the distribution of the electrical potential in the ionization layer, see figure 5.
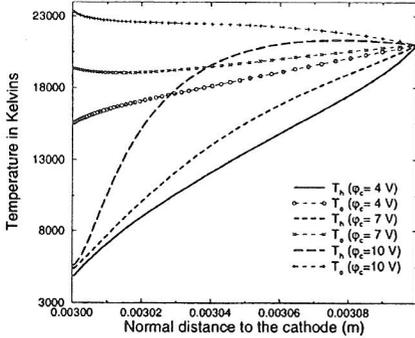
Figure 4: Variation of the temperatures of electrons and heavy species in the ionization zone as a function of the normal distance to the cathode and the cathodic fall
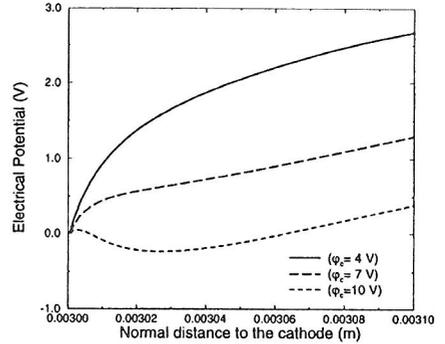
Figure 5: Variation of the electrical potential in the ionization zone as a function of the normal distance to the cathode and the cathodic fall

Finally, the cathode region model presented in this paper has been applied in a two-dimensional simulation of an electric arc including the electrodes. In order to be able to compare the numerical predictions with experimental data, a case which was studied by Hsu et al. [5] has been chosen. In this computation the cathode layer is coupled to the arc column and the cathode in such a way that the continuity of the temperature, the electrical potential, the energy flux and the current density are satisfied at each external boundary limit $(S_0 \ \& \ S_2)$. Therefore, the common temperature of electrons and heavy species and the current density at the (ionization zone-arc column) limit are not fixed here but are results from the thermal and electrical coupling arc-cathode. The simulations of the whole arc-electrodes system have been carried out for $(\varphi_c = 4V)$, $(\varphi_c = 7V)$ and $(\varphi_c = 10V)$. It is found that the maximum temperature in the arc column increases with the cathodic fall resulting in a deviation from experimental results for the cases $(\varphi_c = 7V, \varphi_c = 10V)$. On the other hand, the potential drop between the electrodes is found to be $(21.9V)$ for $(\varphi_c = 4V)$, $(24.4V)$ for $(\varphi_c = 7V)$ and $(26.5V)$ for $(\varphi_c = 10V)$. From this calculations, one can conclude that the cathodic fall $(\varphi_c = 4V)$ reproduces the experimental results both for the temperature field in the arc column, see figure 6, and for the potential drop between the electrodes as the experimental value is about $(22V)$, see Hsu et al.[5].
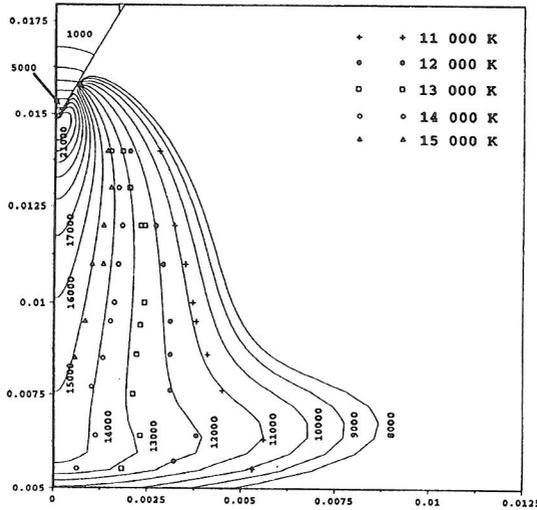
Figure 6: Temperature fields in the cathode and in the arc column obtained for an one centimeter free burning arc simulation with a total current of 200 A. The marked points correspond to experimental data.

Summary

The approach used in the present work allows to go deeply in the study of arc-cathode interaction mechanisms. The results presented here, show that, if the emission mechanism is fixed, all the critical parameters of the cathode layer can be calculated self consistently. Therefore, such an approach can be used to derive the most appropriate emission mechanism in an arc discharge for both thermionic and non-thermionic cathodes. This direction is currently investigated.

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