

## Modeling of Metal Vapor Ionization Processes in the Cathode Spot of a Vacuum Arc

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**Annotation.** In this paper the model of the cathode spot of a vacuum arc is considered in the framework of the drift-diffusion representation. It is shown that the main source of electrons, providing the current transport of vacuum arc, are ionization processes in the cathode zone, while the emission processes are an auxiliary source of initial electrons. The effects associated with the distribution of electron density in the plasma column of cathode spot, in particular the formation of a “plasma reaction zone” and “ionization wave”, are discussed.

For proper developing the techniques and methods for producing nanopowders in the plasma of low pressure arc, it is important to understand the processes occurring in the cathode spot and parameters that have the greatest influence on the physical and chemical properties of nanopowders [1-12].

In this paper the model of the cathode spot of a vacuum arc is considered within the drift-diffusion representation. All the studies showed that the arcs have much in common with the spark discharges, [13] however, the traditional models of Townsend avalanche-streamer mechanism of plasma production cannot be applied due to the short length of the cathode spot.

The system of differential equations has been solved in the *Comsol* software package by the finite element method.

Since all the processes in the cathode spot are defined with characteristic time intervals of 5-100 ns, then the solution of the problem of ionization is sufficient for solving the drift-diffusion Nernst-Planck-Einstein equations, supplemented by the Poisson equation, neglecting the processes of plasma formation, electrical neutrality, etc. That allows revealing the influence of the separate mechanisms of ionization on the structure and dynamics of the cathode spot.

$$\left\{ \begin{array}{l} \frac{\partial n_e}{\partial t} + \text{div}[-D_e \nabla n_e - \mu_e n_e \vec{E}] = v_{ion}(E)n_e - v_{att}(E)n_e - c_{ee}n_en_+ + S_{ph} + S_{un} \\ \frac{\partial n_+}{\partial t} + \text{div}[-D_+ \nabla n_+ - \mu_+ n_+ \vec{E}] = v_{ion}(E)n_e - c_{ee}n_+n_e + S_{ph} + S_{un} \\ \Delta \varphi = -\left(\frac{e}{\varepsilon_0}\right)(n_+ - n_e); \vec{E} = -\nabla \varphi \end{array} \right. ,$$

where  $n_e$ ,  $n_+$  are concentrations of electrons and ions, respectively,  $\varphi$  is the electric potential. The source function for the electrons is defined taking into account the appearance caused by impact ionization with a frequency of  $v_{ion}(E)$ , losses after the adherence with a frequency of  $v_{att}(E)$ , and losses at the electrons and ions recombination with the coefficient of  $c_{ee}$ . The source function for positive ions is defined taking into account their appearance caused by the

impact ionization and their losses at the electrons and ions recombination (factor  $c_{ee}$  is set for the latter value).

The influence of photoionization was neglected for revealing the influence of different sources of ionization on the structure and dynamics of the cathode spot ( $S_{ph} = 0$ ,  $S_{un} = 0$ ). The ions and electrons concentration flows, defined as  $N_e = -D_e \nabla n_e - \mu_e n_e \vec{E}$ ,  $N_+ = -D_+ \nabla n_+ - \mu_+ n_+ \vec{E}$ , consider the diffusion and drift component respectively.

Since these intervals are not more than 10 ns, thus during this time, according to the equation shown above, the ions are displaced up to 1  $\mu\text{m}$  [14], Therefore, the diffusion and ion mobility in the fields, which are not too high, can be considered as constant and equal to  $3.7 \cdot 10^{-3} [\text{m}^2/\text{s}]$ .

Assuming that arc discharge contains no negative ions (as evidenced by numerous studies) the sticking coefficient can be neglected.

The coefficient of recombination of electron with simple ions ( $c_{ei}$ ) has the main channel of recombination called dissociative. Constant value of  $c_{ei}$  equal to  $10^{-13} \text{ m}^3/\text{s}$  was assigned for simulation, since it varies insignificantly in the investigated range of the electric field intensity.

In this model nonstationary one-dimensional problem with a uniform field was solved. The electrons were emitted from the cathode and this process was constant in time. The emission of electrons was taken into account in the form of insignificant ( $10^{-16} \text{ m}^{-3}$ ) initial concentration on the boundary cathode-metal vapor. It was assumed that the emission electrons are the seed particles to start the main ionization processes. Ionization and recombination processes took place in the gap and were taken into account as a reaction rate. The initial concentration of the ions was defined according to the potential decrease across the gap and was located in the ionic cloud zone. The initial concentration of ions and electrons in the discharge gap was zero.

The boundary conditions for the cathode zone are presented in the form of:

$$-\vec{n}[-D_e \nabla n_e - \mu_e n_e \vec{E}] = 0, \quad -\vec{n}[-D_+ \nabla n_+ - \mu_+ n_+ \vec{E}] = 0.$$

The boundary conditions for the ionic cloud zone were taken from the conditions of ionization and recombination, and also diffusion and drift processes in the discharge gap. They can be represented, for example, as follows:

$$-\vec{n}[-D_e \nabla n_e - \mu_e n_e \vec{E}] = N_{0e}, \quad -\vec{n}[-D_+ \nabla n_+ - \mu_+ n_+ \vec{E}] = N_{0+},$$

where  $N_{0e}$  and  $N_{0+}$  are time-constant values for the flow of ions and electrons.

Let's analyze the main stages of the development of the arc discharge. The figures show the development of the arc discharge at different points in time. Fig.1,a shows the change in the concentration of electrons emitted by the cathode in the process of moving to the ion cloud. The number of electrons in it gradually increases under the influence of impact ionization, and the radius of the cloud increases due to the diffusion. The bulk charge is too small for significant changing the electric field that is the initial phase.

Two electron density peaks are clearly seen during the development of the arc discharge. The first peak is the main and is observed in the cathode zone, while the second is observed near the ion cloud. The appearance of the second peak is caused by the first few electrons reached the ion cloud. Because of the diffusion some separate electrons reach it before all the other electrons. These electrons lead to a rapid increase in the concentration right at the ion cloud due to a high field intensity near ions and as a consequence, due to a

high ionization rate. This peak rapidly exceeds the first one by magnitude and becomes noticeable on the background in the moment of time  $t = 2.8$  ns. Nevertheless, since the rate of ionization processes is much higher than electron drift rate, the first peak begins to grow rapidly and they become equal at a moment of time of 4.2 ns.

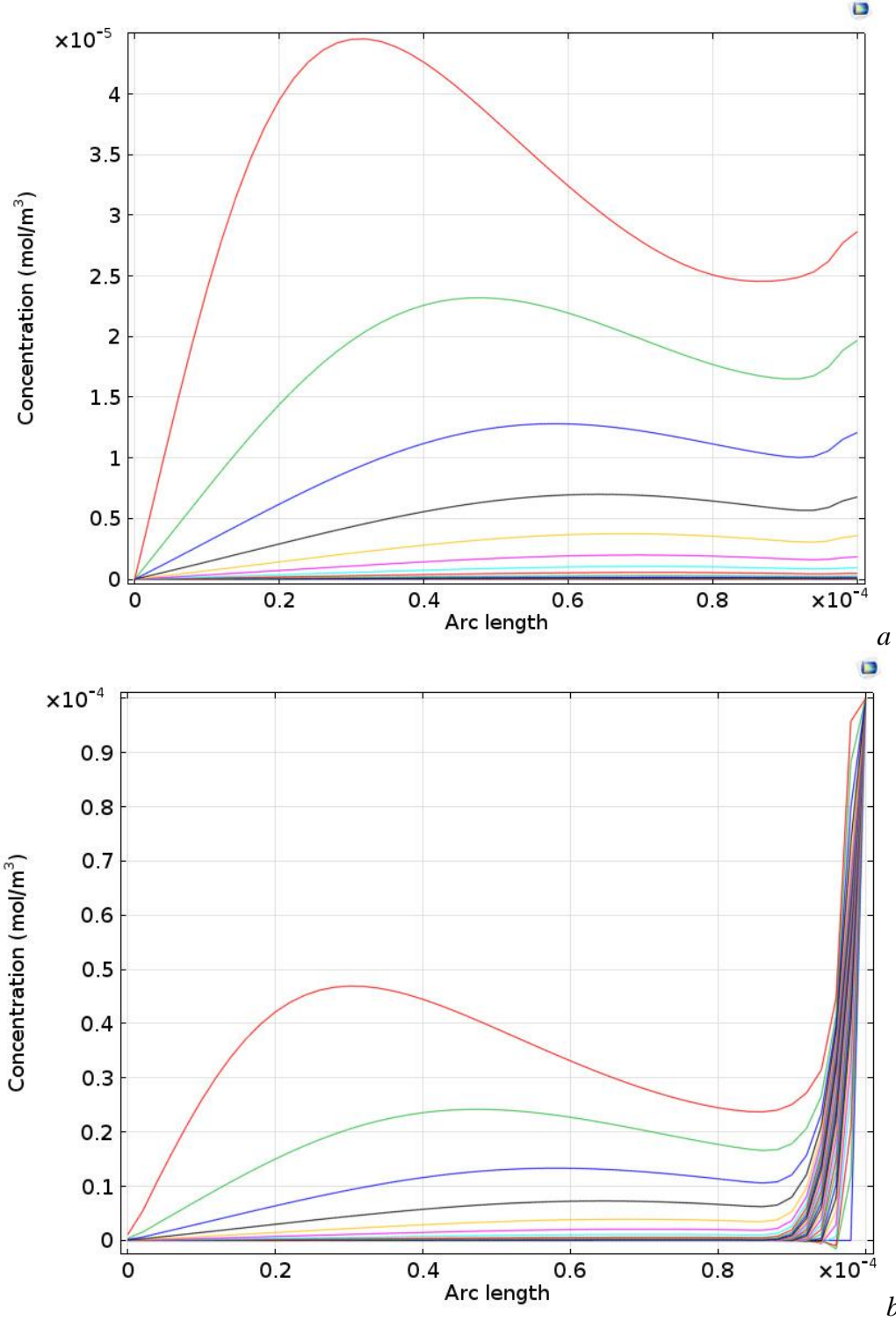


FIG. 1. Electron (a) and ion (b) concentration in the cathode zone in the time intervals of 2 to 5 ns in increments of 0.1 ns

Due to intense ionization in the cathode layer, the uncompensated positive charge is gradually accumulated (Fig. 2), and begins to influence the external electric field, displacing it from the zone of increased concentration of electrons to the boundary of this zone. The zone with increased ionization is also moved there. This leads to increasing the concentrations of ionized particles before the boundaries (Fig. 1,b). Thus the zone of high concentration of charged particles changes its border again. Electron cloud starts to spread towards the cathode from the ion cloud. From this point it can be called "reflected" electron cloud. At this time the state of the zone with high concentration of electrons changed to the plasma state –the field is displaced from here, the bulk charge is practically zero.

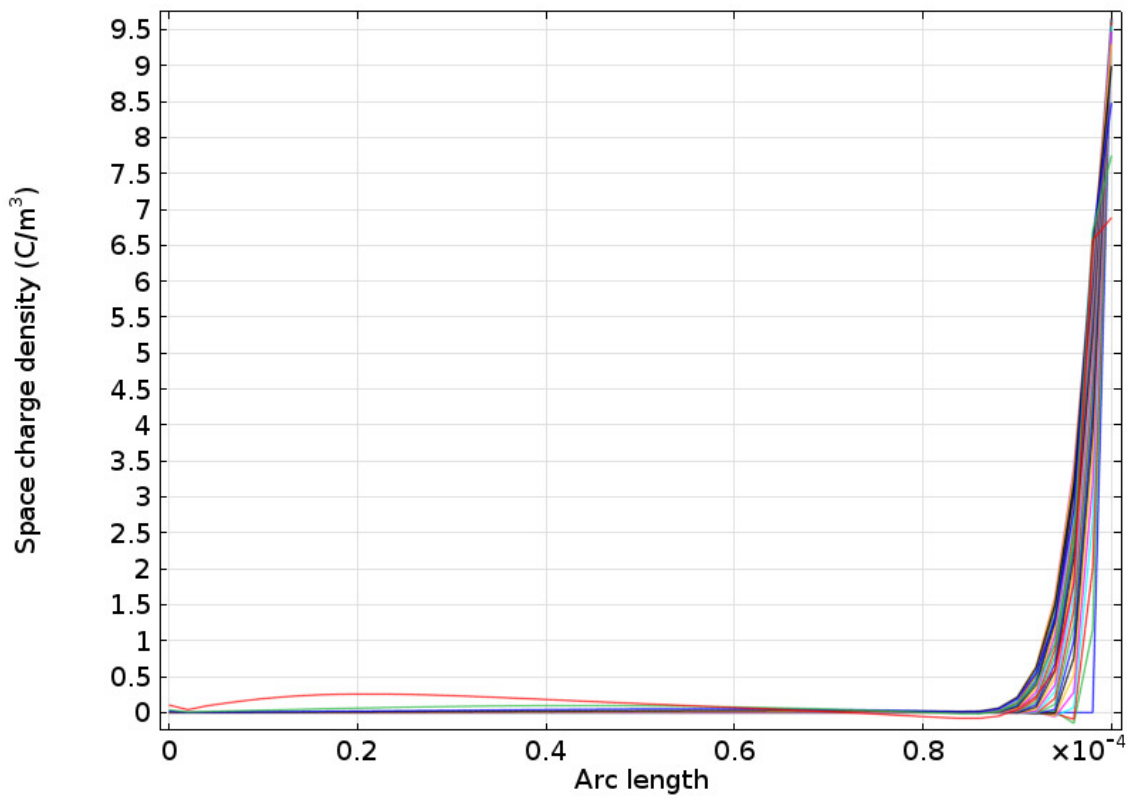


FIG. 2. The diagram of distribution of the bulk charge [ $\text{C/m}^3$ ] in the cathode zone at the moments of time of 2 to 5 ns in increments of 0.1 ns

The above-stated correlates the current understanding of the formed cathode spot structure, which is characterized by the plasma channel, and its field is displaced to the outer boundary of the channel [14,15]. The field peak in this case is located at the front boundary between the cathode zone and the ion cloud. If the arc is developed in the field formed by the electrodes, practically not having changed it, then since the formation of the plasma channel the conductive zone is developed at the expense of the newly formed plasma, deforming this field and forming a “plasma reaction zone” [16,17]. These peaks become new centers of the ionization processes where emission electrons are involved as seed electrons. A new plasma zone with high concentration of electrons ionization is generated as a result of ionization, which lengthens and narrows the plasma channel, displacing the electric field. The ionization wave moves as described above.

The rate of arc current increase is the rate of ionization wave, which can be much higher than a rate of ions move [18].

The field intensity in the plasma channel is less than in front of it. The field intensity it is too low and the impact of ionization in the channel does not occur. The key role is played by the loss of electrons due to recombination process.

In this paper the structure of the plasma column in the uniform field has been calculated within the computer model of the cathode spot. The principle advantage of this model is use of the least possible number of equations to describe all the basic parameters of the cathode spot of a vacuum arc discharge.

It has been shown that the field intensity of the plasma column is significantly reduced the column is surrounded by the bulk charge of the slow positive ions, providing high field intensity in front of it. At the stage of a plasma reaction zone ionization of the metal vapor is predominantly carried out in a thin layer in front of the ions cloud, while ion recombination predominates in the column. Ionization provides a constant elongation of conducting plasma column and moving the bulk charge layer on the outer boundary of the current state, i.e., towards the cathode. This, in turn, leads to a displacement of the local maximum of the electric field and to the displacement of the zone of intense ionization, and provides the movement of the so-called ionization wave.

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