On plasma jet formation in vacuum arc with composite cathode

D L Shmelev¹, S A Barengolts², I V Uimanov¹, M M Tsventoukh³, K P Savkin⁴

¹ Institute of Electrophysics, RAS, 106 Amundsen St., Ekaterinburg, 620016, Russia
² Prokhorov General Physics Institute, RAS, 38 Vavilov St., Moscow, 119991, Russia
³ Lebedev Physical Institute, RAS, 53 Leninsky Ave., Moscow, 119991, Russia
⁴ Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk 634055, Russia

E-mail: shmelev@iep.uran.ru

Abstract. This paper deals with the computer modeling of vacuum arc with composite multicomponent cathode. This arc is typical for certain kind of ion sources, plasma generator and vacuum interrupters. The described hybrid model treats the electrons as an inertialess fluid and ions as macroparticles. The macroparticle dynamic is calculated with the use of particle-in-cell method. Ion-ion Coulomb collision is considered with the use of Monte Carlo method. The model can simulate vacuum arc as a whole including separate cathode plasma jets, mixing zone, and common plasma column. The dependence of ion angular current distribution on the cathode composition reproduced with the help of developed model agrees well with experimental results.

1. Introduction

Research on plasma produced by vacuum arc remains an area of certain scientific interest in plasma physic [1, 2]. This plasma is used for various technical applications [2]. In particular, the vacuum-arc-produced metal plasma is used in ion sources [3-6] to produce intense ion beams for ion implantation, in plasma generator for coating deposition and in high-current interrupters [7, 8]. In order to produce the multielement ion beam or to form the composite metal coating the vacuum-arc-produced plasma from composite multicomponent cathode is used.

Recently, it has been found [3, 4] that ion angular distributions in the plasma jet of vacuum arc are different for the various ion types. Moreover, the angular distribution of ions in the plasma arc with a pure (single component) cathode differs from the angular distribution for the same type of ions in an arc with the composite cathode [3].

The dependence of the angular distribution from the charge of the ion can be explained by the inhomogeneous distribution of electron temperature in the region of strong ionization in the vicinity of the cathode spot. However, the dependence of the angular distribution on the composition of the cathode is difficult to explain as well. It is assumed that the angular distribution of ions in arc plasma is formed under the influence of the mixing of the plasma jets originated from the separate group-spots. However, the simulation of mixing the plasma jets presents some difficulties because this process can not be described in the framework of magnetohydrodynamic approach. In the area of the
mixing zone the ion velocity distribution strongly deviates from Maxwell distribution. A suitable
choice in this case is to use a hybrid model [8], which describes the electron subsystem as a massless
fluid, but ions are described as macroparticles with the help of the particle-in-cell approach. Thus, the
motivation of the present work is to try to reconstruct the experimental [3, 4] ion angular distributions
with the help of the newly developed hybrid model, which is able to simulate the separate jets of
multicomponent plasma from cathode spots, the mixing of the jet and the common plasma column.

2. Model description
A two-dimensional hybrid model was developed to study the formation of the plasma jet originating
from the composite cathode. According to the hybrid approach the electron subsystem is described as
an inertialess fluid, but ions are described as macroparticles. The developed model is analogous to
model [8], but the described model is modified to account for the dynamics and interaction of the ions
of various masses and charges. The governing equations in case of the 2D axial symmetrical geometry
are the following:

\[ \frac{d n_i}{dt} = \nabla \cdot \mathbf{V}_i; \quad m_i \frac{d \mathbf{V}_i}{dt} = e_i \mathbf{E} + \frac{e_i}{c} \mathbf{V}_i \times \mathbf{B} + \frac{m_i n_i \mathbf{a}_i - \nabla n_i}{\tau_{ei}}, \quad (1) \]

\[ n_j = \frac{1}{H_c} \sum_{x=x_i}^{x=x_f} S(x-x_i); \quad \mathbf{a}_i = \frac{1}{H_c} \sum_{x=x_i}^{x=x_f} \mathbf{V}_i S(x-x_i), \quad (2) \]

\[ n_e = \frac{1}{e} \sum_{i} e_i n_i; \quad \mathbf{a}_e = \frac{1}{e n_e} \left( \sum_{i} e_i n_i \mathbf{a}_i - \mathbf{j} \right), \quad (3) \]

\[ \frac{\partial B_{\theta}}{\partial t} + \frac{\partial u_{\theta} B_{\phi}}{\partial z} + \frac{\partial u_{\phi} B_{\theta}}{\partial r} = \frac{c^2}{4\pi} \left( \frac{\partial}{\partial r} \left( \frac{1}{r \sigma} \frac{\partial B_{\phi}}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\sigma} \frac{\partial B_{\theta}}{\partial \phi} \right) \right), \quad (4) \]

\[ \mathbf{j} = \frac{c}{4\pi} \nabla \times \mathbf{B}, \quad \mathbf{E} = -\frac{\nabla \mathbf{P}_{\mathbf{e}}}{e n_e} - \frac{1}{c} \mathbf{a}_e \times \mathbf{B} - \frac{m_i}{e} \sum_{i} \frac{\mathbf{a}_i - \mathbf{a}_e}{\tau_{ei}}, \quad (5) \]

where \( \mathbf{V}_i \)—velocity of ion (of type \( i \)) macroparticles, \( r_i \)—ion macroparticles radius vector, \( S \)—shape
function of macroparticle (bilinear interpolation was used), \( H_c \)—form factor of cell, \( N_c \)—number of
macroparticles in cell, \( n_i \)—ion density, \( n_e \)—electron density, \( u_i \)—ion drift velocity, \( u_e \)—the electron
drift velocity, \( \mathbf{j} \)—total arc current density, \( \tau_{ei} \)—electron-ion collision time, \( \sigma \)—plasma (Spitzer)
conductivity, \( \mathbf{B} \)—magnetic field (only \( \theta \) component exists in a given geometry), \( \mathbf{E} \)—electric field,
\( \mathbf{P}_{\mathbf{e}} \)—electron pressure. It is assumed in addition that electron temperature \( T_e \) remains constant during
the calculation for simplicity.

The macroparticles undergo ion-ion Coulomb collisions. These collisions have been considered
with the help of Monte Carlo method [9].

Two types of cathode boundary conditions (CBC) are tested to analyze the influence of CBC of
certain types on the plasma jet formation. The first type of boundary conditions (CBC-1) is
conceptually identical to supersonic CBC used in the computer models of high current vacuum arc [7].
It is assumed that the numerous individual plasma jets from the separate cathode spots mix together in
extreme vicinity of the cathode surface to produce one common plasma jet with the averaged laminar
ion flux. Practically it means the specification of one solid cathode attachment zone with the effective
current density, which is defined as a total arc current divided by the area of the attachment zone.
Plasma parameters (velocity, charge composition, temperature) at the boundary are assumed to be
identical to the parameters typical for the cathode spot plasma. The plasma density is obtained from
the measured specific erosion. In addition, it is assumed that the cathode attachment zone emits ion
flux in a cone with the angle of \( \pi/2 \).

The second type of the tested cathode boundary conditions (CBC-2) is constructed to represent
certain distribution of the cathode group-spots over the cathode surface. The arbitrary distributed small
attachment areas at the cathode (let us call it a quasi-spot, in order not to confuse it with the real group-spot) emit current and ion within the certain angle. The parameters of plasma emitted from the quasi-spots are the same as in the case of CBC-1. The cathode surface between the quasi-spots only absorbs ions.

The cathode attachment areas (quasi-spots), which emit the plasma jet, mimic the cathode group-spot. In the present calculations the simplest two-spot arrangement is used (Figure 1). Actually the spot 1 has a circle shape but the spot 2 has a ring shape (because of axial symmetry). The spot 2 mimics a number of separate group-spots surrounding the spot 1. The lateral dimension of the quasi-spot and the distance between them are visible in Figure 1. Effective current density in the quasi-spots (for total current 500 A) is about of $10^6$ A/cm$^2$. Current densities through the cathode attachments in the case of CBC-1 and in the case of CBC-2 are equal.

The position of the quasi-spot is fixed during the calculations. In principle the hybrid model is a nonstationary one. Hence, it is possible to model the moving spots. But currently we are modeling a “snapshot” of arc for simplicity (like in [8]).

3. Results and discussion

Results discussed in this section are obtained for arc plasma with composite cathode Zn$_{0.4}$Pb$_{0.6}$. For this cathode the following initial values are used: initial velocity for Zn – $1.15\times10^6$ cm/s, for Pb – $0.55\times10^6$ cm/s [3]; charge state composition for Zn – 80% Zn$^+$, 20% Zn$^+$, for Pb – 36% Pb$^+$, 64% Pb$^+$ [3]; specific erosion for Zn – 54.5 µg/C, for Pb – 172.8 µg/C [6]; ion temperature – 0.5 eV for all types; electron temperature – 2.5 eV [2].

Typical steady state spatial distribution of ion density for CBC-2 is shown in Figure 1. That is the summarised density of all ion components. It is seen that the plasma jets originated from the separate sources (Spot 1 and Spot 2) mix together and produce one common jet at a distance less than 0.2 from the cathode. In general, the mixing takes place at a distance comparable with the size of the cathode attachment.

At the mixing area the kinetic energy of ion counter-streams (originated from different spots, see Figure 2) is converted to chaotic energy by means of ion-ion coulomb collision. Due to this an average effective temperature at the mixing zone reaches 20 eV (for the case shown in Figure 1). After mixing, the jet expands so that the effective ion temperature decreases rapidly. At the distance of 1.5 mm from the cathode the ion temperature decreases to 0.5 eV. The ions of different types heated up at the mixing zone come to local thermodynamic equilibrium (at least in certain volume). Thus, the light ions (Zn in our case) get higher chaotic velocity than the heavy ions. Further, during the common jet expansion the light ions should expand faster than the heavy ions. Particularly, this effect should be
more evident along a line which has a certain angle with the jet axis. The ion density relatively slow decreases along the axis so that the ion-ion interaction will equalize more effectively the velocities of ions of different atomic weights. The heavy ions, compensating the momentum that gone with the light ions should expand more slowly than it was in case of one-component cathode. The calculations made with the help of our model prove the described scenario.

Angular ion flux density distributions shown in Figure 3 and Figure 4 are calculated at the distance of 1 mm from the cathode center (Figure 1). It is seen that in the case of CBC-1 (solid attachment, no jet mixing) the curves of angular distributions of different ions differ in amplitude but have a similar shape. In the case of CBC-2 (Figure 4) the shape of light ions flux distribution is noticeably different from the shape of heavy ion flux distribution. The comparison of calculated angular distributions with ones obtained in [3] is shown in Figure 5 and Figure 6. In accordance with the experimental results the calculated distribution of Zn is wider for composite cathode than the same distribution for one-component cathode. For Pb ions (Figure 6) the agreement with the results of [3] is observed though it is not so clearly as in the previous case. Thus, the jet mixing in front of the cathode attachment affects the ion current angular distribution properly.
Angular distributions of average ion velocity for ions of various types are shown in Figure 7. It is seen that the velocities of different ions are close at the angles less than 45 degrees and differ from each other at the higher angles. The reason for this is the ion-ion coulomb collisions. In the vicinity of the jet axis the ion density decreases slower than at the jet periphery (see Figure 1) so that the ion-ion collisions keep effectiveness at small angles for longer distance. At the jet periphery the ion-ion collisions are ineffective but electron-ion interaction (last term on RHS in (1)) seems to be excessively effective. Probably it indicates certain restriction of the developed model.

The results shown in Figures 4-7 were obtained in assumptions that Zn and Pb ions have different initial velocities \((1.15*10^6 \text{ cm/s} \text{ and } 0.55*10^6 \text{ cm/s})\) respectively [3]). It is roughly means that the cathode spot size is less than the pure element grain so that ions of different elements are produced in different cathode spots at a certain distance from each other. If due to some treatment the mixture of elements is improved then the ions of the different elements can be produced in one cathode spots. In this case the ions of different mass will have the same average velocity due to very strong ion-ion collision in dense cathode spot plasma [10]. In the framework of the model of [11] the calculated average velocity of Zn-Pb plasma was \(0.61*10^6 \text{ cm/s}\) for all ion types. It is necessary to clarify that the ions originated from the cathode spots have quite a wide distribution of kinetic energy [12]. This is in agreement with ecton theory [1, 13], which declares a cyclic behaviour of the cathode spot phenomena. At different stages of the cycle the ions emitted from the spot have different drift velocities, but at any stage the ions with different charges have the same drift velocity [14]. From this viewpoint the velocity obtained within the model of [11] can be treated as a velocity averaged over the ecton cycle [1, 13]. The ion flux angular distributions calculated for this case are shown in Figure 8. The comparison with previous results shows only weak dependence on the ion initial velocity. This effect confirms the important role of jet mixing in the formation of common ion flux from composite cathode.

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