MODELING OF CONTRACTED AND FREE-BURNING ELECTRIC ARCS BETWEEN CONSUMABLE ELECTRODES. 1. ASSUMPTION OF EQUILIBRIUM STATE OF PLASMA

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The role of transfer processes in the formation of a self-organized structure of the plasma of electric arcs is analyzed. The models of contracted and free-burning electric arcs between consumable electrodes are characterized on the whole, by depending on the accepted state of plasma in the discharge channel: equilibrium or nonequilibrium one. In particular, we consider the common channel model and its modifications, including the ellipsoidal one, which use the assumption of equilibrium plasma and allow one to calculate the properties of electric arc plasma. The reasonability of involving the mechanisms of self-organization for the study of the electric arc properties is demonstrated. A method based on the introduction of an effective stabilizing wall (a quasiwall) in the analysis of the plasma processes running in free-burning electric arcs is substantiated.

1. Introduction

An electric arc is one of the first artificially produced objects of plasma physics known since the beginning of the XIX-th century. Even at that time, the unique properties of arcs caused their active penetration into technological processes. The most well-known among them is the electric-arc welding [1]. At that stage, the empirically obtained information on the properties of arcs was sufficient.

By the middle of the 20-th century, electric arc plasma already represented a well-studied object in the conception of its equilibrium state [2]. In the 1960s–1980s, some publications indicated the manifestations of nonequilibrium properties of electric arc plasma [3–7], but those works weren't systematically proceeded. In the 1970s–1980s, two groups of French researchers used the effect of the so-called "demixing" for the explanation of the properties of electric arc plasma between copper electrodes in air [8–11]. Later on, the theory of this process concerning, in particular, the most interesting mixtures for gas discharge physics was elaborated by the Australian scientist A. Murphy [12, 13].

The most amazing fact is that one haven't succeeded till now in the adequate description of the energy balance of some kinds of electric arcs [14]. Meanwhile, new areas of applications of electric arc plasma related, for example, to the energotechnological processing of carbon-bearing materials [16], in particular the processing of wastes including toxic and medical ones, are developed [16]. The power of separate blocks of such facilities amounts to hundreds of kilowatts, whereas their working life is determined just by the electrodes the arc is closed on. That is why the further investigations of electric arc plasma are not only of purely physical but also of practical interest from the viewpoint of the further increase of the efficiency of the technologies based on electric arcs.

2. Transfer Processes in Electric Arc Plasma. Method of Quasiwall

Arc discharges is the form of electric discharges in gases, where the cathode drop has a relatively small magnitude of the order of the ionization potential E_i of atoms of the plasma-forming gas, i.e. approximately 10 V [17]. They are characterized by significant currents ($i \sim 1$–10^5 A) that considerably exceed the typical currents in other kinds of discharges. For example, currents in glow discharges are usually much lower ($i \sim 10^{-4} \div 10^{-1}$ A);

they are also characterized by a high cathode drop (about 100 V and higher).

Thus, one of the undoubtful advantages of an electric arc is its high energy efficiency, speaking in modern language. This fact actually underlies its numerous technological applications. Indeed, an arc allows one to transmit great currents in the gas atmosphere or metal vapors (produced at the expense of the erosion of electrode surfaces during the running of the discharge current – one of the examples of self-organization) at a relatively small voltage or, drawing an analogy to the criteria of energy efficiency for electrical power systems, small power losses in their transport. These advantages are caused by the optimal combination of the surface (in other words, near-electrode and near-wall) and bulk properties of plasma in the current-carrying arc channel [18].

Indeed, the temperature of heavy particles in plasma in the case of their removal from the cathode (wall) varies from the temperature of the cathode to the value characteristic of the bulk of plasma in the surface layer of a small thickness [19]. For example, the thickness of this layer amounts to ~ 0.04 mm in the electric arc in argon at the atmospheric pressure [20]. The maintenance of a constant pressure in the cross section of the arc is reached due to the increase of the concentration of a heavy component in the layer, which leads, in turn, to a considerable attenuation of particle fluxes and heat loss on the wall confining the plasma volume (electric arc channel) [21]. In the above-mentioned case of the arc in argon, these fluxes are depressed by a factor of up to 2×10^{-2}.

In this respect, one of the most important bulk properties is the self-absorption of the resonance radiation. The estimates [18,22] demonstrate that, for the most widespread plasma-forming gases at the atmospheric pressure and the characteristic temperature $T^* \sim 0.1E_i$, the free path of the resonance radiation amounts to 10^{-4}–10^{-2} cm. That is, it is considerably lower than the characteristic radius of an arc $r_a \sim 10^{-1}$–1 cm. The same range of parameters is also typical of plasma in vapors of the most widespread metals at the pressure $p \sim 0.01$ atm, which approximately corresponds to their content in electric arcs generated by consumable electrodes. Thus, quanta of the resonance radiation which are generated in the bulk of an electric arc numerously participate in the formation of a radial structure of the arc in the process of their diffusion in its bulk before they are emitted at the arc periphery. From the viewpoint of thermophysical properties, this phenomenon decreases the huge energy losses, which would be typical of an electric arc in the absence of the self-absorption of radiation and would considerably exceed the actual losses of the electric power in the arc channel, by orders of magnitude.

Summing up the results of investigations of the bulk and surface thermophysical properties of electric arc plasma, it is worth emphasizing that the assumption concerning its equilibrium properties and minimal losses for the transfer of electric energy in the arc channel are interconnected [18]. However, in the case of nonequilibrium plasma, the self-absorption of radiation can result in another effect. For example, as early as in the 1960s, the overpopulation of the resonance level of plasma-forming particles was observed in the case of arcs in argon with the potassium admixture at the atmospheric pressure [3]. This fact can be interpreted as the evidence for a deviation from the equilibrium state of plasma which is usually *a priori* assumed in electric arcs at such a pressure.

At the same time, even the removal of this relatively low thermal energy released in an electric arc due to the passage of the electric current is often problematic and restricts the possibility of its stable maintenance. This fact follows from the Elenbaas–Heller equation that determines the temperature distribution both within the region of existence of an arc and beyond it:

$$\frac{1}{r^{\upsilon}}\frac{d}{dr}\left(r^{\upsilon}\frac{dS}{dr}\right)+\sigma E^2=0; \quad S=\int\limits_0^T \lambda\left(T\right)dT, \qquad (1)$$

where $\nu = 1, 2$ corresponds to the cylindrical or spherical geometry of the problem, r denotes the radial coordinate, $\sigma(T)$ is the electric conductivity, E is the electric field in the arc channel, T is the temperature, and λ is the thermal conductivity. The heat flux potential S introduced here allows one to smooth the influence of the thermal conductivity coefficient which is, in the general case, an irregular function of the temperature that is subjected to the differentiation in Eq.(1). The boundary conditions are as follows:

$$dS/dr|_{r=0} = 0; \quad S|_{r=r_w} = S_w. \qquad (2)$$

Here, the index 'w" corresponds to the cooling wall that surrounds the discharge at some distance (this will be discussed below in more details). The problem concerning this wall is rather fundamental in the electric arc physics. Indeed, in the simple case of a discharge of the cylindrical form, it is impossible to obtain the solution of Eq.(1) in the "plasma–surrounding gas" system with the following substitution of the second boundary condition (2):

$$S|_{r=\infty} = S_\infty, \tag{3}$$

where S_∞ characterizes the temperature of a gas undisturbed by the electric arc. The reason lies in the fact that the removal of the heat flow from the central zones of the electric arc to its periphery cannot be provided under conditions of an insignificant temperature gradient. Indeed, the heat flow through an arbitrary concentric cross section beyond the limits of an arc at a distance r from its axis amounts, by definition, to

$$q = -2\pi\nu r^\nu \lambda(dT/dr) = -2\pi\nu r^\nu (dS/dr). \tag{4}$$

Integrating the expression for the flow in the cylindrical geometry over the region from the arc radius r_a, within which the heat release is concentrated, to some $R > r_a$, we obtain the thermal energy removed from the arc:

$$Q = 2\pi[S(r_a) - S(r)]/\ln(R/r_a). \tag{5}$$

From here, it follows that $Q \;\; \rightarrow 0$ at $R \rightarrow \infty$, i.e. the magnitude of the heat flow that can be removed by the mechanisms of thermal conduction from an open cylindrical arc logarithmically decreases down to zero. A similar peculiarity characterizes the diffusion processes.

This problem is basically absent in the case of spherical geometry ($\nu = 2$ in Eq.(1)): here the gradients at any distance from the source are sufficient to ensure the corresponding transport processes due to the influence of the geometric factor. However, strictly speaking, a spherical arc is not realized.

Due to these circumstances, an open electric arc can usually exist in the form of a rather short arc, whose length does not exceed its several diameters. In this case, the problem of heat removal is solved self-consistently with regard for the geometric factor: the arc acquires the form of an ellipsoid of rotation that approximates its geometry to the spherical one, by facilitating the heat removal in this way [14]. In this aspect, the cylindrical and spherical models can be considered as the boundary cases of real electric arcs.

In the case of a long arc, the problem can be actually eliminated by the arising convective flows in the gas atmosphere, where the arc – a cylindrical heat source – is maintained. However, the possibilities of the energy removal at the expense of convective mechanisms are rather limited [14]. That is why the attempts to lengthen a short arc usually resulted in the unstable mode of its burning and in its extinction. Thus, the problem of heat removal is a risk factor possible to violate the processes of self-organization in electric arc plasma.

In practice, the problem of the unstable burning of an electric arc is often overcome by the use of the above-mentioned cooling or – in the more general aspect – stabilizing walls, to which the heat and diffusion flows from the region of a proper arc are removed. By analogy with the interaction of diffusion flows with surfaces, for example in vacuum evacuation systems, a related effect is that of a “freezing” wall with respect to its interaction with products of the erosion of electrodes.

In the case of the stabilization of an arc by the wall, there appears a basic possibility for two forms of a long arc discharge to exist: volumetric and contracted ones. In the former, the arc column occupies the whole cross section of the cylindrical wall more or less uniformly. In the latter, the discharge is contracted into a relatively narrow filament due to, for example, its ionization-overheating or thermal instability [17,23]. The stabilizing factors are the diffusion and the heat conductivity that facilitate the leveling of a nonuniformity of the particle concentration and the temperature; their relative role decreases with increasing pressure and current strength.

At present, the analytic methods of determination of the parameters of contracted discharges are quite well developed [23–25]. On the other hand, they could be an object of the investigations of the processes of self-organization, as all the preconditions for their presence are available in this case: nonlinearity of the problem, nonequilibrium (unstable) medium, bifurcation point (beginning of contraction as a function of the discharge current of the arc or its pressure), and hysteresis effect [26]. Indeed, the problems of modeling of open arcs are related, to a great extent, to the insufficient study of the mechanisms of their self-organization. At the beginning of this section, some “completeness” of the properties of electric arc plasma with respect to the diffusive, thermal, and radiation losses was already emphasized. The basis for their description is the Elenbaas–Heller equation (1). As for open arcs, their adequate analysis requires the allowance for the convection, geometric factor, cooling effect of the electrodes, etc. Thus, simulating the existence conditions of plasma in such an arc, one needs to concentrate on the heat removal conditions that are secondary with respect to the proper arc. The problem becomes still more complicated in the case of a consumable-electrode arc (which is typical of the given work), as similar problems also arise under study of the diffusion flow of the electrode material vapors.

That is why, considering the analytic investigations of the most general properties of plasma in the channel of an open electric arc, we proposed the method of a quasiwall, according to which any mechanisms of cooling of an arc, which are dependent on its specific geometry or a spatial orientation (the latter influences the efficiency of convective mechanisms), are replaced by the action of some effective wall [27]; it is also "freezing" with respect to the diffusion flow of a metal vapor from the region of contact of the arc with consumable electrodes. This method allows one to use simple equations for the analysis of processes in the external region of the arc channel of cylindrical geometry. Moreover, in whole, it is naturally coordinated with the so-called channel arc model (see below). Earlier, we also demonstrated that the processes running in the channel of an electric arc with evaporating electrodes are mainly influenced only by the nearest peripheral region [28].

Copper that is a plasma-forming substance enters the arc region due to the partial evaporation and the erosion of a material of consumable electrodes. As the temperature in the arc channel is higher than that at the periphery, the propagation of vapors along the arc channel is facilitated (even without considering the so-called cathodic jets of the erosive material [29]). Indeed, the diffusion coefficient D_a for atoms amounts to [17]

$$D_a = \lambda_a v/3, \tag{6}$$

where λ_a is the free path of atoms, v is their average thermal velocity, moreover, $\lambda_a \sim N_a^{-1} \sim T$, a$v \sim T^{1/2}$; thus, $D_a \sim T^{3/2}$ (N_a is the concentration of atoms). Therefore, the atoms diffuse along the arc channel much easier than in the relatively cold region beyond the arc. This fact allows one to consider the channel approximately as a mass source, whose power is determined by the discharge current (in terms of the erosion coefficient of electrodes). The indicated source finally ensures the propagation of copper vapors in the direction of the absorbing quasiwall.

3. Equilibrium Models of Electric Arc

At present, the models based on the assumption of an equilibrium state of plasma in an electric arc are absolutely predominant. This fact is confirmed, for example, by the recent review concerning the modeling of arc discharges [30]. This assumption objectively agrees with the fact of the minimization of losses from the bulk of electric arc plasma mentioned in Section 2 (we recall that just the loss of particles or energy of plasma out of its volume represents the original cause for the non-equilibrium state – in the same way as for any other open system [26]). In particular, this assumption allows one to adequately describe the parameters of the gas plasma of an electric arc between a hot cathode and a cold anode (i.e. nonevaporating one; the arc is closed on such an anode in the diffusion state, by resembling, on the whole, a flame) [31, 32]. One can expect that, in such dense plasma of rather extensive dimensions, where the gradients of the parameters are inessential, the nonequilibrium effects will be insignificant. However, even under these conditions, the mentioned modeling requires the use of rather complicated numerical methods of calculation.

As for the contracted and free-burning arcs between consumable electrodes, it is now more reasonable to use simplified methods of description of plasma properties. Somewhat running ahead, it is worth stressing that the discrepancy between the approaches to the modeling of electric arcs are caused by the significant difference in the influences of the gradient effects: in consumable-electrode arcs, their influence is maximal due to the minimal dimensions of such arcs. The same can be true for contracted arcs between stabilizing walls. It is hard to expect the equilibrium of plasma under such conditions taking into account that it is the gradient effects that represent the original cause for the violation of the equilibrium state [18]. Even the neutral gas in a neighborhood of the arc can deviate from the equilibrium, as it experiences a significant exciting influence of plasma at least via the irradiation mechanism.

C h a n n e l m o d e l. The main problem concerning the analysis of Eq. (1) is the nonlinearity of the real function σ(S). The channel method selects two basic temperature zones in the electric arc region, namely the high-temperature channel, where $\sigma_c = \sigma(T_c)$ and $T_c = T(0)$, i.e. the temperature in the channel is equal to that at the arc axis, and the zone beyond the channel, where $\sigma = 0$ [17,33]. This approach allows one to obtain simple analytic relations between the discharge current, channel radius, parameters of the cooling wall, and plasma temperature.

Q u a s i c h a n n e l m o d e l represents a further improvement of the channel model. It eliminates the main internal contradiction of the latter that lies in the presence of a heat flow along the radius of the arc in the absence of the temperature gradient. In the same way as in the previous model, the region of existence of the arc is divided into two zones: that of the channel $0 \leq r \leq r_a$, where the arc conduction is concentrated $\sigma \neq 0$, and the external nonconducting zone $r_a \leq r \leq r_w$, where $\sigma = 0$. However, the temperature in the central conducting zone is not assumed to be constant over the cross section of the arc [33,34]. The electroconductivity in the conduction zone is chosen on the basis of the relation

$$\overline{\sigma} = \int_{S_a}^{S_0} \sigma dS/(S_0 - S_a). \tag{7}$$

The distribution $S(r)$ in the both zones is searched for by solving the balance equation with the following boundary conditions: $S_I(r_a) = S_1; S_{II}(r_w) = 0$ (where the lower indices "I" and "II" correspond to the thermal potential at the channel boundary and at the wall, respectively). It has the form

$$S_I(r) = S_0 - \overline{\sigma} E^2(r^2/4), \quad S_{II}(r) = S_1 \frac{\ln(r/r_w)}{\ln(r_a/r_w)}. \tag{8}$$

Thus, the distribution $S_I(r)$ in the conduction channel of this model is parabolic (whereas $S_I(r) = S_0 =$ const) in the channel model).

Using the sewing conditions at the interface

$$S_I(r_a) = S_a; \quad \left.\frac{dS_I}{dr}\right|_{r=r_a} = \left.\frac{dS_{II}}{dr}\right|_{r=r_a}, \tag{9}$$

relation (8) yields the expressions for the electric field strength

$$E = 2/r_a[(S_0 - S_a)/\overline{\sigma}]^{1/2} \tag{10}$$

and for the radius of the conduction zone

$$r_a = r_w \exp[-S_a/2(S_0 - S_a)]. \tag{11}$$

The equality of the supplied electric power $P = Ei$ and the heat flow at the interface $Q = -2\pi r dS/dr$ implies the expression

$$i = 2\pi r_a[\overline{\sigma}(S_0 - S_a)]^{1/2}. \tag{12}$$

Thus, five independent parameters of an electric arc present in this model, namely i, E, r_a, r_w, and S_0 appear to be related by three equations (10)–(12). The electric current i and the radius of the absorbing quasiwall r_w are set, whereas the quantity S_a is chosen for a certain temperature range on the basis of the approximate equality $\sigma(S_a) \approx 0$.

The obtained solutions are analytically evident and are used further for the estimation of the influence of various processes taking place in the electric arc.

M u l t i l a y e r (q u a s i c h a n n e l) m o d e l supposes the division of the cylindrical arc region into an aggregate of coaxial layers with constant conductivity and specific radiation in each layer [33,34]. Finally, the solution of the problem is reduced to the use of the method of step-approximation. As a matter of fact, the previous model represents a special case of this one.

T w o-t e m p e r a t u r e (q u a s i c h a n n e l) m o d e l considers the presence of a small parameter $E_i/T_e \ll 1$ in the exponent in the Saha equation that describes the equilibrium plasma, where E_i is the ionization potential of plasma-forming atoms, and T_e is the electron temperature [23]. With the use of this fact, the indicated exponent is expanded into a series by the Frank-Kamenetskii method [35], and the following dimensionless parameter is introduced:

$$\theta = [T_e(0) - T_e(r)]E_i/2T_e^2(0). \tag{13}$$

Eventually, this allows one to essentially simplify the solution of Eq. (1) and to obtain two relations between such measurable parameters as the power of heat generation P, the arc radius r_a, and the gas pressure and the physical parameters T, T_e, N_a, and N_e at the arc axis. In this approach, the arc radius weakly depends on the radius of the stabilizing wall.

This model allowed one to adequately describe the peculiarities of the arc contraction in a plasma mixture which are rather difficult for analysis (inert gas and copper vapors) [25].

In view the final aim of the present publication, it is worth noting that the difference between the temperatures of the heavy and electron components $T<T_e$ finally worsens the conditions of heat dissipation from the electric arc channel [36].

E l l i p s o i d a l m o d e l. The physical presence of a cooling wall represents the main peculiarity of the channel model. This fact eliminates its application to the analysis of processes running in open electric arcs. We developed a rather simple model of a spheroidal symmetric stationary arc proposed in [37] for the description of the properties of an open electric arc in copper vapors [14] previously investigated in our experiments [38]. This model absolutely logically follows from the observations of the external form of short electric arcs between consumable electrodes. In [14], it is shown that, on the whole, the thermal conductivity with regard for the geometric factor approaching the spherical geometry and the mechanisms of generation of convective flows cannot ensure the removal of heat released in the arc channel from the arc region at high temperatures of plasma in the channel (or at high discharge currents). The authors consider that the reason for such a disagreement with the fact of the existence of short electric arcs under conditions of great currents lies in the assumption about the equilibrium of plasma in their channels.

4. Conclusions

The above-described models of an electric arc based on the assumption about the equilibrium state of plasma in the arc channel repeatedly proved their ability to predict and explain properties of the electric arc plasma in many cases of practical importance.

Nevertheless, by concluding the first part of the work, we presnt a simple convincing example of the boundedness of such models. It is the attempt to determine the pressure in the plasma channel of a free-burning electric arc between consumable electrodes on the basis of both the results of experimental measurements of the temperature and the concentration of electrons and the Saha equation, i.e. on the basis of the assumption about the equilibrium. As a rule, it gives a result significantly exceeding the atmospheric pressure which is one of the external, easily and accurately controlled parameters of an arc. It is just the phenomenon we confronted with at the beginning of our experimental investigations of the physical properties of arcs in copper electrode vapors [39].

As early as then, in order to explain the observed effects, we proposed a mechanism of plasma nonequilibrium which is based on the transfer of radiation from the axial hottest region of the arc to its periphery. This results in the overpopulation of the resonance level of plasma-forming atoms. However, in order to explain the same set of the observed effects, French researchers [9–11] proposed another mechanism which consists in the separation of the copper vapor – nitrogen mixture in the channel.

An unbiased estimation of the possible role of the both mechanisms will be performed in the following part of the work.

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МОДЕЛЮВАННЯ
КОНТРАГОВАНИХ ТА ВІЛЬНОПІДТРИМУВАНИХ ЕЛЕКТРИЧНИХ ДУГ МІЖ ПЛАВКИМИ ЕЛЕКТРОДАМИ.
1. НАБЛИЖЕННЯ РІВНОВАЖНОГО СТАНУ ПЛАЗМИ

В.А. Жовтянський, Ю.І. Лелюх, В.М. Патріюк

Р е з ю м е

Аналізується роль процесів перенесення у формуванні самоорганізованої структури плазми електричних дуг. В цілому характеризуються моделі контрагованих та вільнопідтримуваних електричних дуг між плавкими електродами залежно від прийнятого стану плазми в розрядному каналі: рівноважного або нерівноважного. Зокрема, розглянуто поширену каналову модель та її різновиди, а також еліпсоїдну модель – моделі, що використовують уявлення про рівноважну плазму та дозволяють розраховувати властивості електродугової плазми. Показано доцільність залучення механізмів самоорганізації для вивчення властивостей електричних дуг. Обґрунтовується метод введення ефективної стабілізуючої стінки (квазістінки) в задачах аналізу плазмових процесів у вільнопідтримуваних електричних дугах.