THE TRANSPORT OF THE EROSION PRODUCTS OF ELECTRODES IN ELECTRIC ARCS

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Electrodes vapour material transport characteristics in the free-burning electric arc and formation of its pressure gradients are investigated. It is shown that adequate defining of gas-dynamic characteristic of electric arc plasma demands successive account of the thermal conductivity processes in the channel arc region. The roles of the gas-dynamic and diffusion processes as transfer mechanisms of electrodes erosion products are compared. The method using distant stabilized wall to study the transfer processes out of channel proposed.

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1. INTRODUCTION

Comparing with other forms of gas discharge the electric arc is characterized with minimum loses of energy on the transport of electricity within it's channel. This property designates the wide application of electric arc plasma in modern high-technologies. Particularly it concerns the electric arcs, free-burning between melting electrodes in gas atmosphere, where the properties of plasma in arc channel are defined by metal vapours resulted from the products of electrodes erosion. Gas atmosphere, where the electrodes are located, represent practically inert component of plasma, because the ionization potential of metal atoms is, as a rule, smaller than the gas one [1]. Further the metal vapours, coming through neutralization processes, diffuse into the ambient space.

In numerous investigations of free-burning arcs between melting electrodes in the gas atmosphere at some pressure p_∞ (as a rule $p_\infty=1$ *atm*) the pressure a priori is considered to be constant along the arc radius *r*, both in the arc channel and outside: $p(r)=p_\infty=const$. The validity of such assumption from the view point of the dynamics of originated stream of metal vapours is analyzed below.

2. THE TRANSFER PROCESSES IN THE ELECTRIC ARCS

The electric arc of approximately cylindrical shape, initiated between flat faceplate melting electrodes with small inter electrode distance, is investigated. As the plasma properties almost exclusively defined by metal vapours [1, 2], it is possible in the first approximation to consider the most general dynamic properties of erosion product flows on the example of it transport into their own atmosphere.

The essential feature of concerned system is principal absence of the solution for the transport equations (diffusion and thermal conductivity) for cylindrical type of arc [2,3]. At the level of the general properties of electric arc the unstable regime of burning of long arc discharges corresponds to this state. Truly, as a result of single integration of expression for thermal flux density ω for cylindrical source

$$\omega=-2\pi r\lambda\cdot (dT/dr) =-2\pi r\cdot(dS/dr) \qquad (1)$$

(where λ – thermal conductivity coefficient, T – temperature, $S=\int_0^T \lambda(T)dT$ – thermal potential) in the region from the arc channel R to $r>R$ the value of thermal flux Q from unit of length can be obtained. It equals:

$$Q=2\pi r[S(R)-S(r)]/\ln(r/R). \qquad (2)$$

So if $r\to\infty$ then $Q\to 0$, so the thermal flux, which can be transferred due to the thermal conductivity from cylindrical source decreases to zero logarithmically. The same feature is characteristic for the diffusion processes. This limitation vanishes for the spherical source: here because of influence of geometrical factor the gradients are sufficient to provide the corresponding transport processes. It is especially essential, that for distances from axis $r>L$ of any electric arc, where L – its length, the problem becomes spherically symmetrical. So there is no sense to consider the problem in cylindrical geometry for $r\to\infty$ (more precisely when $r>L$). At the same time the problem for spherical source is independently interesting related to formation of erosion products stream on the electrodes surface (electrode spots). Here the inflow of electrodes material vapour into the arc channel takes a place practically in the point source regime and has a character, close to hemispherical flow.

In the strict sense due to the influence of thermal conductivity processes the arc often shapes near to ellipsoidal, especially in so-called short and transition types of arcs [3]. In this aspect it is possibly to consider cylindrical and spherical sources as a extreme cases of real source existence.

In practice the problem of unstable functioning of electric arc is solved often by application of so-called stabilized walls where the surplus thermal and diffusion fluxes are "freezing". Ordinary they are in contact with electric arc plasma. In the experiments [1, 2], where the stabilized wall was absent physically, their role actually plays convection, which take off mention thermal and diffusion fluxes, initialized in the arc channel.

3. THE DYNAMIC OF ELECTRODES EROSION PRODUCTS

In contrast to transfer process the gas-dynamic problem for the ideal gas flow from a cylindrical source, as in the case of spherical one, has a solution [4]. In this connection the considered here problem of gas-dynamic process investigation has independent interest with relation to study the qualitative influence arising here flow on the general electric arc properties.

It is supposed that the arc channel is a cylindrical source of electrodes material products. The distribution of mass production rate per unit volume is uniform. It is because of the influence of electromagnetic forces on plasma stream at the near electrodes region, where the plasma jet of erosion material take place along the axis of arc (see [5]). Moreover in the arc area the velocity of gas propagation is maximum because of the maximum value of temperature T; it describes by sound velocity

$$a=(\gamma R_0T/\mu)^{1/2} \tag{3}$$

(where R_0 – universal gas constant, γ – ratio of specific heats, μ – molecular weigh of gas). The mechanism of diffusion transfer of metal vapour is the most essential in the arc channel too [3]. The consumption of initial concentration of erosion products in the arc channel corresponds to the upper value of pressure drop on its boundary.

In such form the problem corresponds to channel model of electric arc [6]. In order to obtain the dynamic characteristics of the radial flow of electrodes material erosion products the system of gas dynamics equation was solved in isothermal approximations for the arc channel (mass source) and in the adiabatic approximation for the outside regions.

The continuity equation for the stationary flow is:

$$\rho q=(r/R)Q/\upsilon\pi R^{\upsilon}L^{2-\upsilon},\ r\leq R; \tag{4a}$$

$$\rho q=Q/\upsilon\pi R^{\upsilon}L^{2-\upsilon},\ r\geq R. \tag{4b}$$

Here ρ – density, q – the local flux velocity, υ – geometrical factor, which is: $\upsilon=1$ for the cylindrical geometry and $\upsilon=2$ for the spherical one, R – radius of mass source. In the case of cylindrical source R corresponds to the arc radius, and L – to the inter electrode separation. The erosion rate for mass source is

$$Q=kI, \tag{5}$$

where I – arc current, k – sputtering coefficient, which for the cooper electrodes can reach the value 10^{-5} g/Cl [7]. It is considered that the cathode spot fills with erosion product half-sphere (for $\upsilon=2$) or cylinder of length $L/2$ (for $\upsilon=1$). The equations (4) are correct independently on assumption of isothermal flow.

To obtain the flow parameters the motion equation is used:

$$\rho q dq=-dp, \tag{6}$$

where ρ and q are connected by state equation

$$p=\rho R_0T(1+\alpha)/\mu; \tag{7}$$

here α – is a degree of plasma ionization. For the arcs in the metal vapour

$$\alpha<<1. \tag{8}$$

Taking into account that according to the channel model [6] the regime is isothermal

$$T(r)=T_0=const, \tag{9}$$

as a result of single integration the solution of motion equation for source region is obtained

$$(q_R^2-q^2)/2=R_0T_0/\mu\cdot\ln(p/p_R), \tag{10}$$

where the arc parameters on the channel boundary (where $r=R$) are marked by index "R". Next using the state equation (7), the continuity equation (4a) for $\upsilon=1$ and the equation (3) and (8) follows the flow character in the arc region in an explicit form:

$$\frac{q}{q_R}\exp\left(\frac{q_R^2-q_R}{2R_0T_0/\mu}\right)=\frac{M}{M_R}\exp\left(\frac{M_R^2-M^2}{2}\right)=\frac{r}{R} \tag{11}$$

Here the Mach number is entered

$$M=q/a. \tag{12}$$

The solution for ρ_0/ρ_R it is possible to find by substitution (11) into (4a):

$$\rho_0/\rho_R=exp(M_R^2/2) \tag{13}$$

where the parameter on the arc axis is marked by index "0". Moreover, according to (4a)

$$q_R=Q/(\pi RL\rho_R). \tag{14}$$

It is not difficult to check on that the solution (11) becomes ambiguous on the source boundary $r=R$ if $M_R>1$. It means that here there is the parameters discontinuity – the shock wave (SW) [4]. At the same time the solutions (13) and (14) include the relationship on its front automatically.

The estimations for the typical value of current, corresponding to the SW mode, on the example of free-burning electric arc between cooper electrodes of small radius ($R=1$ mm) with the length $L=3$ mm were made. For the typical values of $M_R=1$ and, correspondingly, $q_R=q=a_0$, and for the typical temperature $T_0=10^4$ K, from the expression (4) and (5) follows:

$$I^*=\pi RL\rho a_0/k\approx 7\cdot 10^4\ A \tag{15}$$

Thus, for the typical arc currents $I\sim 10^2$ A in welding arcs the subsonic regime of erosion products flow is realized.

Concerning the region of arc's "root" at the electrode's surface define interest has a solution of the same problem for the spherical source. For $\upsilon=2$ in (4) we find the typical radius R^* of region, where the intense metal inflow into the electrodes gap takes place:

$$R^*=kI/(2\pi R\rho a_0)^{1/2} \text{ or} \tag{16}$$

$$R^*(mm)=(0.35\text{-}0.45)\cdot[I(A)]^{1/2}.$$

The parameters range in the last expression corresponds to the limit values of cooper content in atmospheric air for arc channel from 0 % to 100 %. This range takes into account the dependence $\rho\sim\mu$ and $a_0=(\gamma/\mu)^{1/2}$, where $\gamma=5/3$ and $\mu=63.5$ for cooper and $\gamma=7/5$ and $\mu=24$ for nitrogen molecules as main component of air.

Thus for the typical values of discharge currents the values R^* is about 1 mm, what is in good agreement with the observed in experiments the radius of intense luminous ball near the electrodes [2].

Concerning the flow dynamic in adiabatic approximation regime for the regions outside of source (e.g. arc channel) the following expression is typical:

$$p/p_R=(\rho/\rho_R)^{\gamma}. \tag{17}$$

It is necessary to underline that adiabatic regime of flow for the arc outside regions is nonrealistic. Really, the experimentally observed temperature ratio is $T_0/T_\infty\sim 30$.

Thus the following ratio of pressure must correspond to this temperatures:

$$p_0/p_\infty=(T_0/T_\infty)^{\gamma/(\gamma-1)}=30^{5/2} \qquad (18)$$

So in the role of agent, who can provide the transfer of thermal energy from every partial unit of erosion products in adiabatic expansion might be the pressure, whose heavy gradient in this case can provide the mass- and heat transfer from arc channel. However such drop isn't natural for the real arcs between melting electrodes in gas atmosphere [1].

In reality another regime is realized: the influence of thermal conductivity prevail in the high temperature region near the arc channel and it solves the problem of thermal transfer. This is like to pulse plasma processes, where SW are replaced often by heat-wave as very effective mechanism to equalize the heavy pressure gradients [2].

4. THE COMPARISON OF THE ROLES OF GAS-DYNAMIC AND DIFFUSION PROCESSES

In the last paragraphs instead of real mixtures of metal vapour (including it's ionized components) and ambient gas, the some effective gas medium with averaged molecular weigh μ of it's components is considered

$$\mu=\Sigma_i x_i\mu_i, \qquad (19)$$

where

$$x_i=n_i/n - \qquad (20)$$

the content of single component with the density n_i in the mixture with the total density n.

However gas-dynamic approach gives no way of deducing the contribution of effects, connected with mixture separation. Really, in electric arc with melting electrodes the diffusion flux to the periphery regions also takes a place [8].

In the general case to the arbitrary mixture of gas and metal vapour it is possible to summarize, that as a result of joint action of gas-dynamic and diffusion processes on the arc boundary the total transfer of metal vapour through unit square to the arc periphery is

$$J_m=x_mJ^G+J_m{}^D=Q/\pi RL, \qquad (21)$$

where according to (14)

$$J^G=q_R\rho_R, \qquad (22)$$

and the $J_m{}^D$ finds according to [8].

In one's turn in the mixture the gradient of gas content $x_g=1-x_m$ determines so that in the conditions of opposite diffusion flux of metal vapour and gas-dynamic flow of mixture as a whole in the laboratory co-ordinates the directed motion of gas component absent. This means that the following expression is corrected:

$$x_gJ^G=(1-x_m)J^G=J_g{}^D. \qquad (23)$$

Here the subscripts m and g refer to metal vapour and gas, correspondingly.

Depend upon the effectiveness of gas-dynamic and diffusive mechanisms of electrode erosion products transfer in the arc the metal vapour content is established, which can be estimated according to (21)

$$x_m = 1- J_m{}^D/J^G. \qquad (24)$$

As a rule in the channel of arc, free burning between melting electrodes, the metal vapour content isn't exceed 1 % [1-4]. This means that the influence of diffusion processes is considerable.

The resume about exceeding influence of diffusion processes is correct only for the arc channel. According to the estimations (16) for the region of arc's "root" on the electrode surface as spherical source of erosion products to the interelectrode space the gas-dynamic processes exceed.

5. THE METHOD OF STABILIZING WALL SEPARATED OF ELECTRIC ARC PLASMA TO STUDY TRANSFER PROCESSES

To take into account nonadiabatic processes in real electric arcs, the numerous calculation of the radial flow of electrodes material erosion products was fulfilled. In this case the radial profile of temperature was adopted from experiment [1]. The result is that essentially the drop of pressure takes place in the region of temperature gradients. It does mean, that the main dynamic processes are grouped nearby arc channel.

To exclude the role of convection, which depends on arc position and has no regular influence on the arc processes, the stabilized wall may be used. Contrary to common electric arc devices, where the plasma is in contact with this wall, in the proposed system the wall should be offset by some distance from the arc.

To study the transfer processes out of channel region this distance due to be satisfy some requirements. On the one hand, the wall due to be on some distance ΔR away from the channel, so the arc was free-burning and on the other hand this distance should not be exceeded a limiting position $R_w{}^{max}$ where this wall still capable take off thermal and diffusion fluxes, initialized in the arc channel.

The basic requirements are follows.

$$\Delta R >> l_w, \qquad (25)$$

where l_w is length of plasma wall layer which consist of 0.04 mm in electric arc argon plasma of atmospheric pressure [9].

$$\Delta R > l_d,\ l_h, \qquad (26)$$

where l_d and l_h are diffusion and heat conductivity lengths.

$$R+\Delta R < R_w{}^{max} \qquad (27)$$

(see above).

$$R+\Delta R < L/2, \qquad (28)$$

where L is length of electric arc (see Sec. II).

Zone between arc channel and stabilizing wall in theoretical treatment may include not only diffusion and heat conductivity processes but also radiation transfer in self-consistent mode.

Another way of looking at this problem is determining $R_w{}^{ma}$ dependly on electric arc plasma parameters. It may be useful to study heat conductivity efficiency in electric arc devices.

The obtained formulations can be used also for the independent electrode material sputtering coefficient k determining based on spectroscopic measurements of it content in the arc channel (as it was made in [1, 4]) taking into account the final dependence this content from the source power Q according to (5). For this aim the special arc device with determined geometry of the electrodes and stabilized walls can be used. This will allow to calculate the influence of transfer processes at most accurately.

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ПОШИРЕННЯ ПРОДУКТІВ ЕРОЗІЇ ЕЛЕКТРОДІВ В ЕЛЕКТРИЧНИХ ДУГАХ

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Досліджуються особливості поширення пари електродного матеріалу у відкритій електричній дузі та формування обумовлених нею градієнтів тиску. Показано, що адекватне визначення газодинамічних властивостей електродугової плазми вимагає послідовного урахування процесів теплопровідності в приканаловій області дуги. Порівнюється роль газодинамічних і дифузійних процесів як механізмів відведення продуктів ерозії електродів. Запропонований метод теоретичних досліджень процесів перенесення з використанням віддаленої від каналу дуги стабілізуючої квазі-стінки.

РАПРОСТРАНЕНИЕ ПРОДУКТОВ ЭРОЗИИ ЭЛЕКТРОДОВ В ЭЛЕКТРИЧЕСКИХ ДУГАХ

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Исследуются особенности распространения паров электродного материала в открытой электрической дуге и формирования обусловленных ими градиентов давления. Показано, что адекватное определение газодинамических свойств электродуговой плазмы требует последовательного учета процессов теплопроводности в приканальной области дуги. Сравнивается роль газодинамических и диффузионных процессов как механизмов отведения продуктов эрозии электродов. Предложен метод теоретических исследований процессов переноса с использованием удаленной от канала дуги стабилизирующей квази-стенки.