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PHYSICAL FEATURES AND DIAGNOSTICS OF THE PLASMA OF A FREE-BURNING COPPER-VAPOR ELECTRIC ARC

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Results of detailed spectroscopic investigations of the spatial structure of the plasma of a free-burning electric arc between copper electrodes are given. A method of adaptive-computational spectroscopy that permits determination of nonequilibrium-plasma parameters is proposed.

An electric arc, being one of the most extensively studied objects of plasma physics, attracts researchers' close attention again. This is objectively demonstrated by the proceedings of the recent International Symposium on Plasma Chemistry [1], a major portion of which was devoted to precisely this object. This is primarily due to the use of plasma of electric-arc origin in various technological devices.

In an electric arc with fusing metal electrodes, electrode material enters the electrode gap by evaporating under the action of the current. Having a low ionization potential as compared to the atoms of the ambient gas (of inert gas, as a rule), metal atoms make the main contribution to provision of the electron concentration in the discharge. In the long run, this has a substantial effect on the processes of heat, mass, and electrom transfer in the plasma. Even an insignificant vapor impurity (about 1%) alters noticeably the electrical conductivity of the plasma over a wide temperature interval [2, 3]. Thus, the basic parameters of an electric-arc plasma are wholly determined by "contaminating" impurities. Furthermore, their presence has an effect on the spatial distribution and magnitude of other basic parameters: temperature, concentration of the heavy component, etc.

As an illustration we note that an electric arc can be initiated between the contacts of switches when high-current electric circuits are broken, which leads to considerable erosion of the contact material. As a rule, the electrodes are made of copper, silver, or gold. The relatively low ionization potential of the atoms of these materials (of the order of 7 eV) also leads here to maintenance of substantial conductivity for the intercontact gap. The indicated situation sharply curtails the operating efficiency of commutating devices.

Experimental works on the study of arc processes have most frequently been performed with wall-stabilized consumable-electrode arcs [2-4]. The use of these devices is convenient in spatial measurements of electric-arc plasma parameters, except for their usual spatial and temporal instability. In this case, we can use comparatively slowly acting (of the order of several minutes) measurement equipment and procedures. However a wall-stabilized arc is only an experimental model of a free-burning electric arc, for example, a welding arc. In particular, the possibility of using this model in determining temperature, impurity content, and electron and heavy-component concentration in real free-burning arcs is doubtful.

The radial distribution of metal vapors in electric arcs between evaporating electrodes has repeatedly been investigated by various groups of researchers. Usually, these investigations are performed by spectroscopic methods within the framework of the assumption of local thermodynamic equilibrium (LTE) in the arc plasma. A stable effect of increase in the vapor content at the periphery of the arc [2-4] in different configurations of electrode gaps immersed in different media (air, nitrogen, helium, and argon) manifests itself. This increase is usually considered to be due to the effect of separation (i.e., demixing) of the components of the plasma generating mixture in the process of ambipolar diffusion. In the plasma of a wall-stabilized electric arc column, temperature and electron-concentration gradients cause ambipolar drift of electrons and ions from the axis to the walls. The flux of charged

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particles is balanced by a flux of neutral particles directed from the periphery to the center of the discharge. Components with a low ionization energy become ionized before they reach the axis. This leads to enrichment of their content in peripheral zones of the discharge. In the experiments performed, it did not exceed 1% in absolute magnitude. To confirm this assumption, the contribution of diffusion processes, which form the basis of this effect, was estimated in [5, 6]. However, in these works, results of spectroscopic measurements that, in determining the radial temperature $T(r)$ and electron-concentration $N_e(r)$ profiles, were processed under the assumption of LTE again were used as the initial data. Meanwhile there are some facts that do not fit into the assumption of the presence of LTE in an electric arc plasma [7, pp. 74-90; 8]. The influence of diffusion on the character of the radial distribution of impurity copper in the plasma of a free-burning electric arc is analyzed in [9]. The results of this work show that allowance for diffusion processes does not lead to distinct features in the radial distribution of metal vapors.

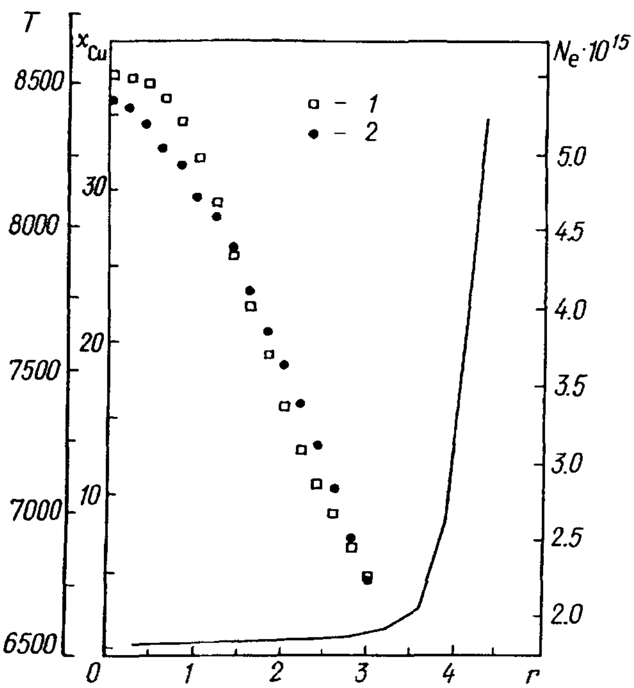
The present work seeks to investigate experimentally the physical features of the plasma of a free-burning copper-vapor electric arc using high-speed measurement equipment and procedures.

The arc was initiated in air between two noncooled copper electrodes 6 mm in diameter; the interelectrode gap l_{ac} was 2–8 mm. To avoid droplet formation, we used a pulsed regime: a current pulse of amplitude up to 100 A and duration 30 msec was applied to a "keep-alive" low-current discharge; investigations were performed in the quasi-stationary stage of the process. The choice of copper is due to the simplicity of the structure of its atom as the subject of spectroscopic investigations, which is comparable in this respect to, perhaps, helium among gases. Because of the space and time instability of the discharge we used the method of single tomographic recording of the spatial intensity distribution for the spectral lines 465.1, 521.8, and 510.5 nm of CuI [10] as well as the absorption coefficient at the center of the latter using a copper-vapor laser [11]. Introduction of a Fabry–Perot interferometer in the optical system of the tomographic spectrometer enabled us to measure spectral-line broadening at different points along the radius during one pulse [10]. High-speed scanning of the spatial and spectral distribution of the radiation intensity was performed by means of an electrostatic dissector, which has considerable advantages over other types of photodetectors [12].

We investigated the radial distributions of the temperature $T(r)$, electron concentration $N_e(r)$, and absorption coefficient $\kappa_0(r)$ at the center of some spectral lines of the free-burning arc plasma. The results of the experiments permit an understanding of the physical processes that occur in this plasma and a study of its spatial structure.

The radial temperature profile $T(r)$ was determined from the ratio of the local emittances of the spectral lines 510.5 and 521.8 mm. These lines had been widely used in previous experiments [2, 3]. The high intensity and sufficient difference in energy of the upper levels (about 3 eV) permit good accuracy of measurement. However in connection with the fact that the lower level of the line 510.5 nm lies rather low (1.39 eV), the measured intensities can be substantially distorted due to self-absorption. Therefore the results of direct temperature measurements can be considered as a first-order approximation.

When the electron concentration is measured, temperature-independent methods are preferred. One of them is based on measurements of the Stark broadening of the spectral line 515.3 nm. Another possibility consists in determination of the absolute intensity of a line emitted from an atomic level of a considerable excitation energy. As is known, the electron configuration of the ground state of a copper atom is $3d^{10}4s$, and the ionization potential of s-electron terms is E_i = 7.724 eV. However the electrons of the d-shell are easily excited and, as a result, a second system of terms (so-called displaced terms) appears whose convergence limit lies above the ionization potential E_i. The displaced terms can be emptied by both radiation and autoionization, which leads to their nonequilibrium population with respect to the s-terms. The spectral line 465.1 nm corresponds to the $5s^4D_{7/2}-4p^4F_{9/2}$ transition, and since autoionization from the $^4D_{7/2}$ level is forbidden [13], its population is determined by the Boltzmann equation. This level's energy is E_s = 7.74 eV; consequently, we can disregard the temperature dependence of the intensity of the line 465.1 nm in measuring by it the radial and longitudinal profiles of the electron concentration N_e:



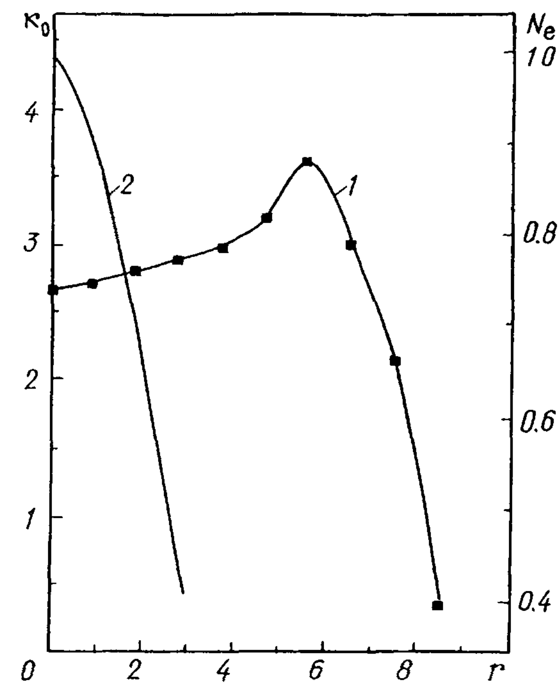


Fig. 1. Radial profiles of the temperature $T(r)$ (1), electron concentration $N_e(r)$ (2), and copper content x_{Cu} for $i = 30$ A and $l_{ac} = 8$ mm. T, K; x_{Cu}, %; N_e, cm^{-3}; r, mm.

Fig. 2. Radial profiles of the absorption coefficient at the center of the spectral line 510.5 nm κ_0 (1) and the relative electron concentration N_e (2) for $i = 30$ A and $l_{ac} = 8$ mm. κ_0, cm^{-1}; N_e, rel. units.

$$I \sim N_e^2 T^{3/2} \exp\left[(E_i - E_s)/kT)\right] \sim N_e^2 T^{3/2} .$$

Furthermore, the self-absorption effect for this line is insignificant, since the energy of its lower level is 5.07 eV. Thus the line 465.1 nm is very convenient for N_e measurements.

The measurements were made absolute using an ÉV-45 high-temperature ($T \approx 4 \cdot 10^4$ K) continuous-spectrum pulsed source. Additionally, the measurements of the electron concentration were controlled by the Stark broadening of the CuI spectral line 515.3 nm.

Radial temperature $T(r)$ and electron-concentration $N_e(r)$ profiles are exemplified for the case of the interelectrode gap $l_{ac} = 8$ mm and of current a pulse $i = 30$ A in Fig. 1. These are radial profiles that are typical of an electric arc. Use of the equation of state enabled us, under the assumption of LTE, to calculate the radial profile of the total concentration of copper atoms and ions $N_{Cu}(r)$. This profile is presented in Fig. 1 in terms of the relative content $x_{Cu} = N_{Cu}/\Sigma N$ (where ΣN is the total concentration of heavy particles in the copper-air plasma); it is characterized, similarly to [2, 3], by an increase in x_{Cu} at the periphery of the arc. The only special feature is that here this increase is much more distinct and amounts to almost an order of magnitude with respect to the axial region. This is apparently due to the different character of the arcs: here the arc is free-burning, while in the cited works it is wall-stabilized. In any case, the result obtained seems nonphysical. The population of the metastable level N_m that is calculated for this regime under the assumption of LTE increases "disastrously," too.

Naturally, both to check the result obtained and to test the applicability of the procedure itself, we need a method that is independent of the plasma state. This is laser absorption spectroscopy, where the population of the absorbing level is determined as

$$N_k \sim \int \kappa(\nu)\, d\nu \sim \kappa_0 \, \delta\lambda ,$$

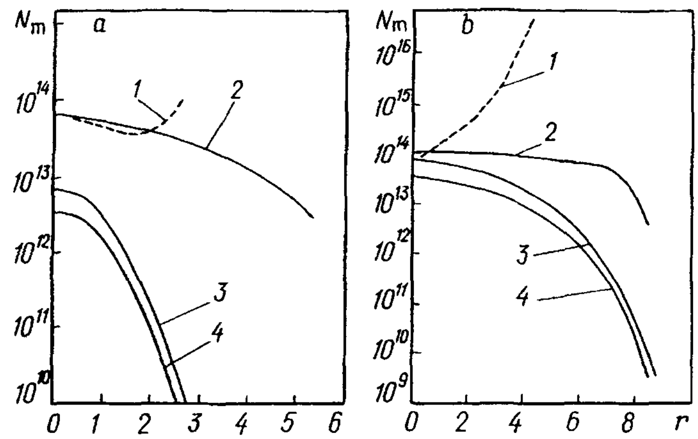


Fig. 3. Radial profiles of the population of the metastable level of copper for l_{ac} = 8 mm, i = 3.5 A (a) and i = 30 A (b) calculated: 1) in the LTE approximation; 2) from measured values of κ_0 under the assumption of the Doppler broadening mechanism ($N_m = 9.2 \cdot 10^{15} \kappa_0 \delta\lambda$); 3) the same, under the assumption of the Stark broadening mechanism with allowance made for the data of [14] ($N_m = 1.2 \cdot 10^{16} \kappa_0 \delta\lambda$); 4) the same, with allowance for the data of [15]. N_m, cm^{-3}.

where κ_0 is the absorption coefficient at the center of the spectral line; $\delta\lambda$ is the line half-width.

The absorption coefficient at the center of the spectral line 510.5 nm was measured by the method of laser absorption spectroscopy using a copper-vapor laser whose generating line corresponds to this spectral line. This procedure made it possible to considerably extend the investigation domain in the radial direction. Here the "shadow" of the arc on the spectrometer's entrance slit in a parallel beam of radiation from the copper-vapor laser was recorded. The absorption coefficient κ_0 at the center of the spectral line 510.5 nm, determined in this manner, turned out to be a distinct quantity in a spatial region that is several times larger in radius than the size of the emitting zone of the arc. In Fig. 2, this zone is arbitrarily shown as the radial profile of the relative electron concentration. From the measured coefficient of absorption at the center of the spectral line κ_0 we can calculate the population of the lower level of this line $N_m \sim \kappa_0 \delta\lambda$ by assuming a broadening mechanism. And since the energy of the lower level of the line 510.5 nm is only 1.39 eV, its population reflects in practice the distribution of the copper-atom concentration.

Figure 3 show radial population profiles for a metastable copper level calculated under the assumption of LTE (1) and from results of measuring the absorption coefficient κ_0 (2–4) for different currents of the arc: 3.5 A (a) and 30 A (b). The broadening mechanisms were assumed to be Doppler and quadratic Stark with broadening constants taken from [14, 15]. The calculations showed that for a low-current arc, when the electron concentration is low, the broadening is governed by the Doppler effect. As the current and, accordingly, the electron concentration increase, the contribution of Stark broadening becomes comparable to the Doppler broadening. On the whole the results presented yield a qualitative difference in the radial profiles of $N_m(r)$ that are calculated under the assumption of LTE and determined from the absorption coefficient. At the same time, in the plasma, there is a region in which both results agree. Consequently, here LTE is realized and it is precisely this that confirms the correctness of the procedures used. From Fig. 3b it can be inferred that the Stark-broadening constant calculated in [14] is preferred. Conversely, at the periphery of the arc we observe a clear disturbance of LTE.

What is the reason for the disturbance of equilibrium? In [16], a two-temperature model of an electric-arc plasma is proposed according to which the electron and heavy-component temperatures do not coincide at the periphery, unlike the axial region. The authors explain the reason for this disturbance of LTE by the fact that the density of electrons in this region is small and, as a consequence, the low frequency of their collisions with heavy particles does not ensure temperature equalization. Without disregarding this possibility we assume that at the periphery of an electric-arc plasma, where the temperature is relatively low, LTE is disturbed due to absorption here of resonance radiation from the high-temperature axial zone. This LTE disturbance manifests itself in

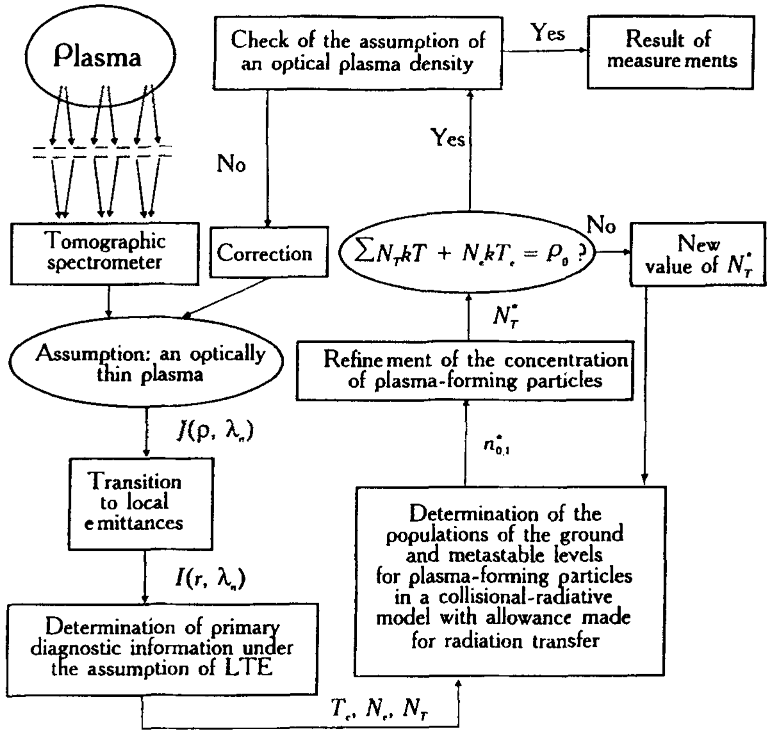


Fig. 4. Scheme of the procedure of computational-adaptive plasma spectroscopy.

overpopulation, with respect to the equilibrium population, of the resonance level of the copper atom. Allowance for this mechanism within the framework of the collisional-radiative model leads to a satisfactory result [9]. Furthermore, this assumption is supported by an analysis of the results of Fig. 3. The existence domain for LTE becomes narrower as the current increases in spite of the fact that the electron concentration increases substantially. Thus, a mere decrease in the plasma density cannot be the reason for the disturbance of equilibrium.

The procedure of computational-adaptive spectroscopy proposed by us earlier [17, 18] makes it possible to adequately determine the plasma parameters of a real electric arc. It enables us to allow for a deviation from LTE and the circumstance that one of the diagnostic lines can be partially self-absorbed. We use as the initial data results of spectroscopic measurements corrected in an iteration process in accordance with the assumed mathematical model of the arc under study (see the scheme in Fig. 4).

Allowance is made for the following components of the copper-air plasma: CuI and NI atoms, CuII and NII ions, N_2 molecules, and electrons. The presence of oxygen atoms and molecules can be disregarded in connection with their small quantity and high ionization potential.

The profiles of spectral intensities of plasma radiation (the integral intensities along the chords) as functions of the distance from the axis $J(\rho, \lambda_n)$ that are observed in the experiment are used as the output data. By solving the inverse problem we transform them to the radial distribution of the emittances $I(r, \lambda_n)$ or temperatures $T(r)$ in the approximation of an optically thin plasma. The initial plasma parameters are calculated in the LTE approximation using the Saha equations for copper and nitrogen atoms, the dissociation equation for nitrogen molecules, Dalton's law, and the equation of plasma quasineutrality. It is precisely this approach that corresponds to the data of Fig. 1. A drawback of the temperature data in it is that the self-absorption of the spectral line 510.5 nm is not allowed for. Meanwhile, a consequence of the latter is two physical effects: deviation from LTE because of radiation transfer and distortion of the intrinsic emittances for this line $I(r, \lambda)$, which are used to calculate the temperature.

In the proposed model of partial local thermodynamic equilibrium (PLTE), the population of the levels can be calculated according to the collisional-radiative model with allowance for radiation transfer in the resonance lines. The following system of kinetic equations is solved:

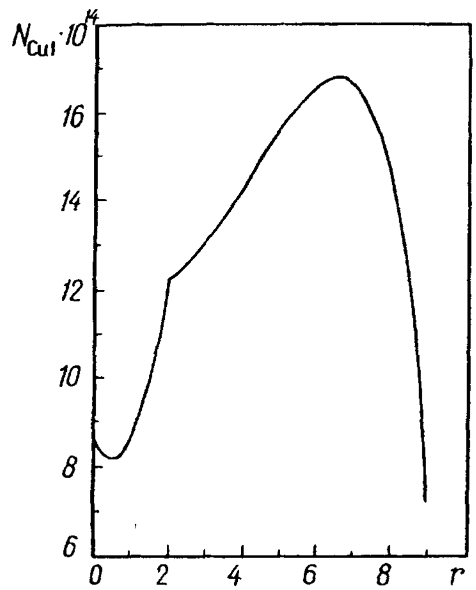


Fig. 5. Calculated radial profile of the copper atom content in the PLTE approximation in an optically dense plasma. N_{Cu}, cm^{-3}.

$$\sum_{i \neq k} (N_i K_{ik} - N_k K_{ki}) = 0 \, ,$$

where

$$K_{ik} = B_{ik} \rho (\nu) + w_{ik} + w_{ik}^{a} \, ;$$

$$K_{ki} = A_{ki} + B_{ki} \rho (\nu) + w_{ki} + w_{ki}^{a} \quad \text{for} \quad k > i \, ;$$

N_k and N_i are the populations of the k-th and i-th levels; K_{ik} and K_{ki} are the total probabilities for the $i \rightarrow k$ and $k \rightarrow i$ transitions, respectively, which involve exitation/deexcitation by electrons w_{ik} and heavy particles w_{ik}^{a} [7], spontaneous absorption, induced excitation, and absorption of intrinsic plasma radiation due to plasma-radiation transfer; $\rho(\nu)$ is the radiation density in the spectral lines, calculated from the equation

$$\frac{1}{c} \frac{\delta I (\nu)}{\delta t} + \vec{\Omega} \cdot \vec{\nabla} \cdot I (\nu) = \kappa' (\nu) \, [I_p (\nu) - I (\nu)] \, ,$$

where $\vec{\Omega}$ is the unit vector that shows the direction of motion of light quanta; $I_p(\nu)$ and $I(\nu)$ are the radiation intensities for a blackbody and the plasma, respectively; $\kappa'(\nu)$ is the effective absorption coefficient with allowance for re-emission,

$$\kappa' (\nu) = \kappa (\nu) \left[1 - \exp \left(- \frac{h\nu}{kT} \right) \right] .$$

The relationship between the radiation intensity and density is given in [19, pp. 7-9, 16-22]. In this manner we calculated the populations of the ground, metastable, and resonance levels; the above-lying levels were considered as equilibrium with respect to the resonance level. The initial populations of the levels of a copper atom are calculated according to Boltzmann's law. The similar calculations involve an iteration process that is continued until Dalton's law

$$N_i^{Cu} + N_a^{Cu} + N_i^{N} + N_a^{N} + N_m^{N} + N_e = P/kT_e$$

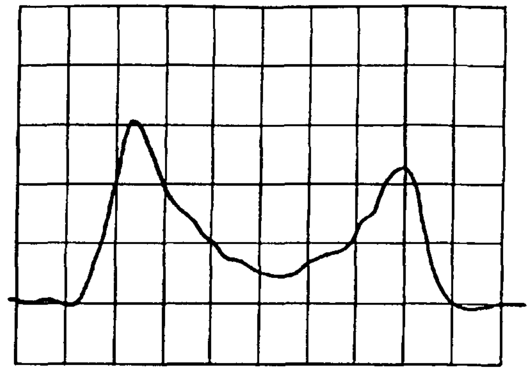


Fig. 6. Oscillogram of the intensity distribution for the spectral line 465.1 nm along the arc channel for i = 30 A and l_{ac} = 8 mm.

and the PLTE model are satisfied at each point along the arc radius. This computational procedure is the first step in the method of computational-adaptive spectroscopy.

The next operation in this cycle is to check the optical thickness of the plasma in the diagnostic spectral lines. The computations are finished if the plasma turns out to be optically thin. Otherwise, the initial values of $I(r, \lambda_n)$ are corrected to the new values $I_k(r, \lambda_n)$ and, hence, the temperatures $T_k(r)$. Next the previous cycle is repeated until the result of numerical integration of the radial emittance distribution along the chords with allowance for radiation transfer coincides with the initial experimental data $J(\rho, \lambda_n)$. Figure 5 shows the result of the calculation of the copper-atom concentration with allowance for the optical density of the plasma under the assumption of PLTE. This result correlates qualitatively with the coefficient of absorption at the center of the spectral line 510.5 nm measured experimentally (Fig. 2).

Figure 6 shows an oscillogram of the longitudinal of the relative intensity distribution of the spectral line 465.1 nm for an interelectrode gap of 8 mm. The observed intensity maxima correspond to the presence, in the electrode regions, of sources of copper vapor that propagate into the interelectrode gap, governing to a considerable degree the spatial profile of the arc.

Consequently, we can speak of the spatial structure of an electric-arc plasma. In the radial direction on the axis, there is a zone in which the particle concentrations are rather high, the temperature is significant, and LTE is realized. At the periphery of the arc in the zone of low plasma density and low temperature, LTE is disturbed due to overpopulation of the lower levels as a consequence of absorption of resonance radiation from the high-temperature central region. In the longitudinal direction, we clearly observe electrode regions with a high content of both electrons and copper vapor. As the interelectrode gap decreases (to 4 mm or less), these regions merge, forming a single zone in which, because of considerable transfer of resonance radiation, LTE must also be disturbed on the axis of the middle cross section of the electric arc.

Thus, the properties of a free-burning copper-vapor electric-arc plasma are governed to a considerable degree by its inhomogeneity.

Owing to the fact that the proposed diagnostic method includes a considerable body of spectroscopic information, it enables us to determine the parameters of a sharply inhomogeneous and nonequilibrium plasma and, on the other hand, to select the spectroscopic constants themselves, as we did earlier in relation to determination of the Stark parameter of broadening of the spectral line 515.3 nm [20]. As far as the authors know, the results presented represent one of the most complete investigations of free-burning copper-vapor electric arcs.

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