INVESTIGATION OF NONEQUILIBRIUM IN PLASMA OF ARC DISCHARGE BETWEEN MELTING ELECTRODES

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In this paper, the different scenarios of experimental data treatment are considered, which may lead to contrary conclusions about the possibility of realization of a local thermodynamic equilibrium in the plasma. In particular, the level of detail of the plasma components of free-burning in air electric arc (in particular, account of molecule of nitric oxide) have an effect on the region of nonequilibrium in the discharge plasma at arc current of 3.5A.

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INTRODUCTION

It is well known, the reliability of switching devices depends on the quality of the electrical contacts, in particular, on the erosion resistance of such contacts' material [1]. Among the factors contributing to the destruction of the contact, first of all, it is necessary to note the arc discharge arising when the inductive load is breaking. Therefore, the special requirements, sometimes contradictory, are introduced to the material of the contacts, the main ones of which are low contact resistance and resistance to erosion [2]. The estimation of erosion resistance can be carried out by direct and indirect techniques. As the last one technique, the measurement of electrode material vapour content in plasma of discharge gap can be considered. Usually, optical spectroscopy is used to estimate the plasma parameters, in particular, concentration of some kind species in plasma. Usually, optical spectroscopy is used to estimate the plasma parameters, in particular, concentration of some kind particles in plasma. In this case, it is important to know whether the plasma is in the state of the local thermodynamic equilibrium (LTE).

It is known that the deviation of the LTE in arc discharge plasma can be caused by various reasons. For example, in paper [3], a deviation from equilibrium is considered due to the overpopulation of atomic levels by radiation (hence, the Boltzmann distribution is disturbed). It is also known [4] that non-equilibrium of plasma can be due to a decrease in the frequency of collisions of electrons with heavy particles (a case of non-isothermal plasma when the Maxwell distributions for electrons and heavy particles are characterized by different temperatures). Under conditions of air plasma of atmospheric pressure, this phenomenon is observed, first of all, at the periphery of discharge. Additionally, the deviations from ionization equilibrium and from the mass action law for the dissociation of molecular gases (which are described by the Saha and Guldberg-Waage equations) can be realized as well [5, 6]. Therefore, the aim of this paper is the study of additional factors, which can be able to have an influence on validity of conclusions about the realization of a local thermodynamic equilibrium in the plasma of electric arc discharge in air between melting electrodes at arc current of 3.5 A.

1. EXPERIMENTAL INVESTIGATIONS

The free burning electric arc at current of 3.5 A was ignited in air between the end surfaces of the non-cooled electrodes [7]. The diameter of the rod electrodes was 6 mm and discharge gap was 8 mm. Electrodes were positioned vertically. The upper copper electrode is used as a cathode, and the lower one (anode) is made of Ag(70 %)-Ni(30 %) composite material [8].

To determine the plasma temperature in [9], the Boltzmann plots method was used. The electron density was determined by solving the energy balance equation [10]. This method involves a preliminary determination of the radial temperature distribution and measurement of the electric field strength of the positive column [11].

Monochromator MDR-12 with 3000-pixels CCD linear image sensor (B/W) Sony ILX526A was used to fast scanning of radial distribution of spectral intensity.

Due to the instability of the discharge, statistical averaging of the recorded spatial distributions of the radiation characteristics was carried out.

2. CALCULATION OF PLASMA EQUILIBRIUM COMPOSITION

The calculation of the component composition of the plasma in the air atmosphere with the impurities of copper, silver, and nickel vapours is performed on the base of the predefined radial distributions of the temperature $T(r)$ (Fig. 1) and the electron density $N_e(r)$ (Fig. 2). In addition, radial profiles of spectral lines' intensities are used. These intensities are measured for spectral lines (Fig. 3) of copper I_{Cu}, silver I_{Ag}, and nickel I_{Ni} in arbitrary units for only one selected wavelength of radiation per element.

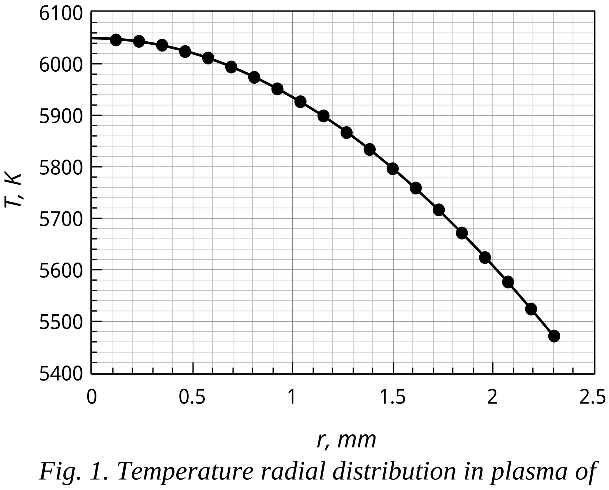

Fig. 1. Temperature radial distribution in plasma of arc discharge of 3.5 A current between asymmetric Cu- and Ag-Ni-electrodes

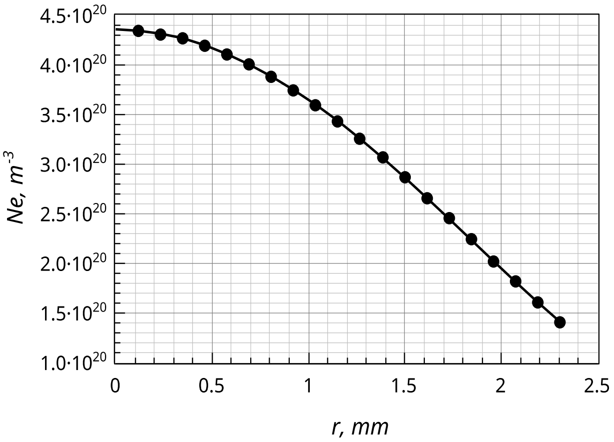

Fig. 2. Electron density radial distribution of electric arc discharge plasma of 3.5 A current between the asymmetric Cu- and Ag-Ni-electrodes

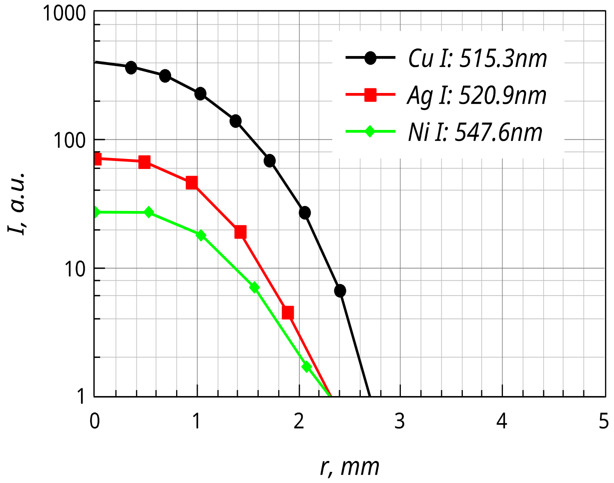

Fig. 3. Radial intensity profiles of spectral lines in the arc discharge plasma of 3.5 A current between asymmetric Cu- and Ag-Ni-electrodes

To calculate the component composition on the base of the aforementioned parameters, the following set of equations is solved.

1) Saha equation:
$$\frac{N_e \cdot N_{A+}}{N_A} = S(T, N_e), \qquad (1)$$

where N_e is the electron density, N_{A+} – the density of ionized atoms or molecules of the species '*A*', N_A is the density of atoms or molecules of the species '*A*', *S* is the Saha function for atomic or molecule of the species '*A*', which takes into account the reduction of the ionization potential in form [12]: $\Delta E[eV] = 6{,}9 \cdot 10^{-9} \cdot \sqrt[3]{N_e[m^{-3}]}$, where *T* is temperature and '*A*' means, in our case, the following atoms and molecules: *N*, N_2, *NO*, *O*, O_2, *Cu*, *Ag*, *Ni*.

2) Dissociation equation for nitrogen, oxygen and nitrogen oxide molecules:
$$\frac{N_N^2}{N_{N2}} = D_{N2}(T),$$
$$\frac{N_O^2}{N_{O2}} = D_{O2}(T), \quad \frac{N_N \cdot N_O}{N_{NO}} = D_{NO}(T), \qquad (2)$$

where *D*(*T*) are the chemical equilibrium constants.

3) Mass conservation for air atmosphere:
$$3{,}72\left(2N_{O2} + 2N_{O_2^+} + N_O + N_{O^+}\right) + 2{,}72\left(N_{NO} + N_{NO^+}\right) = 2N_{N2} + 2N_{N_2^+} + N_N + N_{N^+} \qquad (3)$$

4) The equation of electroneutrality:
$$N_e = N_{N^+} + N_{N_2^+} + N_{NO^+} + N_{O^+} + N_{O_2^+} + N_{Cu^+} + N_{Ag^+} + N_{Ni^+} \qquad (4)$$

5) The perfect gas low:
$$2N_e + N_{N2} + N_N + N_{NO} + N_{O2} + N_O + N_{Cu} + N_{Ag} + N_{Ni} = \frac{P}{kT}, \qquad (5)$$

where *P* – atmospheric pressure.

To solve the system, it is necessary to define additionally the radial profile of the ratio between the densities of various metals atoms. With this aim, the intensities of at least one wavelength λ_{Ag}, λ_{Cu}, λ_{Ni} in the radiation of each metal component in the plasma were experimentally measured in the assumption of Boltzmann population distribution of the atom levels of these metals (that is, one of the requirements of the existence of LTE in plasma). Then, the radial profile of the ratio between the three components in the plasma (silver, copper, and nickel atoms) α(r) becomes as follows:
$$\frac{I_{Ag}\lambda_{Ag}^3 U_{Ag}}{gf_{Ag} N_{Ag}} \exp\left(\frac{E_{Ag}}{kT}\right) = \frac{I_{Cu}\lambda_{Cu}^3 U_{Cu}}{gf_{Cu} N_{Cu}} \exp\left(\frac{E_{Cu}}{kT}\right) = \frac{I_{\mathrm{Ni}}\lambda_{\mathrm{Ni}}^3 U_{\mathrm{Ni}}}{gf_{Ni} N_{\mathrm{Ni}}} \exp\left(\frac{E_{\mathrm{Ni}}}{kT}\right) = \alpha(r) \qquad (6)$$

In order to test the validation of assumption of LTE in plasma, the system (1) – (6) is solved once again with other input parameters: temperature, intensities of the spectral lines I_{Cu}, I_{Ag} and I_{Ni} and the ratio between the components of metals for the axial point of the discharge, which is represented in the form of (6) (i.e., α(0)). The results of the calculation, namely, the obtained radial density profile was compared with the experimentally determined. The spatial region of the discharge in which both profiles coincide (within the error of the experiment) can be treated as equilibrium. The difference between these profiles indicates a deviation from LTE, the reason for which may be the violation of equilibrium processes (not only of Boltzmann distribution, but also can be caused by nonequilibrium of ionization and dissociation processes etc.).

In Fig. 4 the calculated composition of arc discharge plasma with impurities of *Cu*, *Ag*, *Ni* vapour is shown. In Fig. 5 the components that are most important for electrical conductivity are shown. The analysis of Figs. 4, 5 shows that the main source of electrons in the plasma (in this mode) is the thermal ionization not only of the atoms of silver, copper and nickel, but nitrogen oxide molecule as well. That is why, in order to determine the effect of NO^+ ions on the formation of the valid equilibrium zone of discharge (the border of the LTE along the radius of the arc), the calculation was carried out for both cases, namely, with account of this molecule in plasma composition and without it as well.

For comparison, in Fig. 6 the plasma composition is shown without account of nitrogen oxide. One can see, that the increase of metal ions is evident, especially in the arc periphery. In Fig. 7 the components that are most important for electrical conductivity without account of *NO* molecule are shown. In Figs. 8, 9 the calculated electron density without account and with account of nitrogen oxide ions for different sets of spectral line intensities as initial data is shown. Additionally, the profiles of the experimentally determined electron density *exp* N_e and its error (± 30 %), in the form of the upper N_e^{sup} and the lower N_e^{inf} boundary are shown in these figures. Calculated curves of electron density *calc* N_e^1 are obtained with handling of a set of spectral lines *Cu* I 510.5 nm, *Ag* I 520.9 nm, *Ni* I 464.8 nm; and curves *calc* N_e^2 are obtained with handling of an alternative set of spectral lines *Cu* I 515.3 nm, *Ag* I 520.9 nm, *Ni* I 547.6 nm.

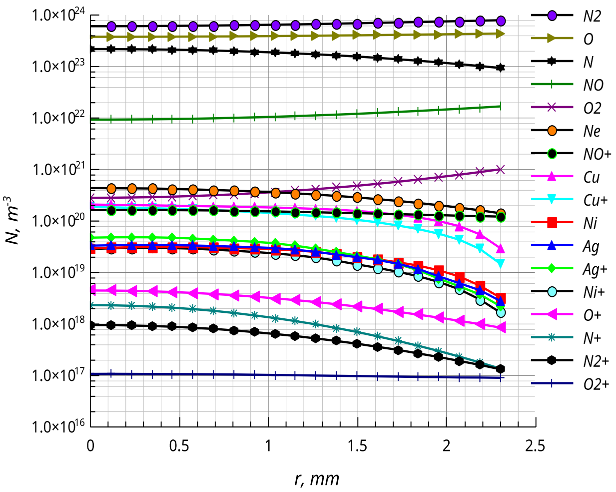

Fig. 4. Component composition of arc discharge plasma with a current of 3.5 A with the impurities of copper vapor, silver and nickel

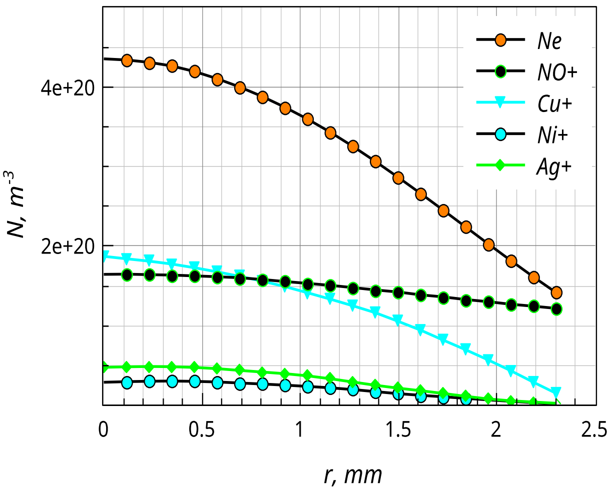

Fig. 5. Electron density and most important ions of arc discharge plasma between composite Cu- and Ag-Ni-electrodes

As it follows from analyze of Figs. 8, 9, in case of the neglecting of nitrogen oxide ions in plasma composition LTE appears to be disturbed at a distance of 1.5 mm from the axis of discharge, whereas, the account of these ions leads to the equilibrium, which remains even up to 2.4 mm. In last case, obviously, the ionization of nitrogen oxide molecule significantly affects the value of the electron density and the realization of LTE in plasma, especially, at the arc periphery.

However, it should be noted that at high discharge currents, in the conditions of temperature increase, the contribution of the ionization of nitrogen oxide becomes not so noticeable.

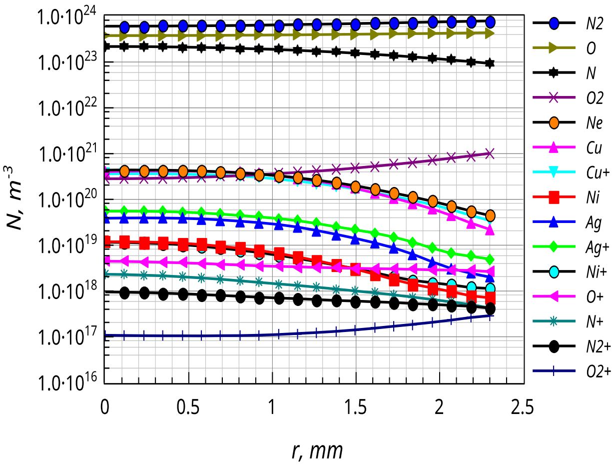

Fig. 6. Component composition of arc discharge plasma with a current of 3.5 A with impurities of copper vapor, silver and nickel without account of nitrogen oxide

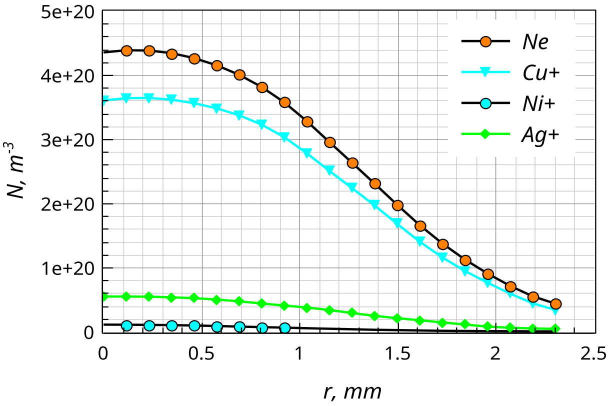

Fig. 7. Electron density and most important ions of arc discharge plasma between composite Cu- and Ag-Ni-electrodes without account of NO molecule

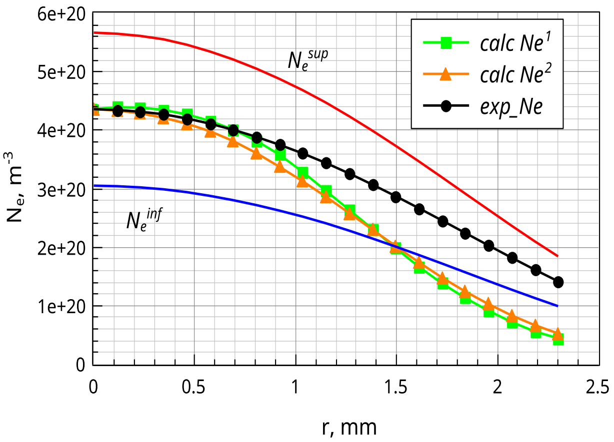

Fig. 8. Electron density of arc plasma of 3.5 A current between Cu- andAg-Ni-electrodes (without account of NO^+)

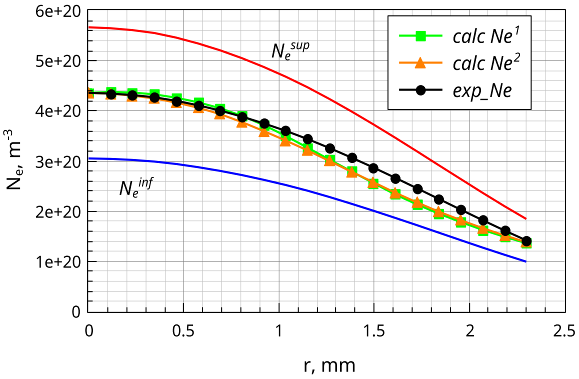

Fig. 9. Electron density of arc plasma of 3.5 A current between Cu- and Ag-Ni-electrodes (with account of NO^+)

CONCLUSIONS

The level of detail of components in the calculation of the plasma composition of electric arc between melting electrodes in the air have an effect on the validity of conclusion on plasma equilibrium in some areas of the discharge. In particular, the account of the *NO* molecule and its ion NO^+ in the plasma composition indicates the realization of the local thermodynamic equilibrium in the relatively low temperature plasma region at the discharge periphery. The account of these molecules is especially important in the study of the thermodynamic state of a plasma of a free-burning electric arc with metal vapour impurities at the current of 3.5 A.

REFERENCES

1. V.Ya. Berent, S.A. Gnezdilov. Improvement of performance of current collectors on the carbon base // *Friction and Lubrication in machines and mechanisms*. 2009, v. 2, p. 18-23

2. V.Ya. Berent, S.A. Gnezdilov. Enhancement of current collectors on the carbon base of electric trains *// Friction and lubrication of machinery*. 2008, № 8, p. 9-15.

3. V.A. Zhovtyansky. Non-equilibrium of dense arc discharge plasma caused by the transfer of resonant radiation // *News of higher educational institutions: chemistry and chemical technology*. 2012, v. 55, № 4, p. 4-9.

4. Yu.P. Raizer. Physics of gas discharge // *Educational manual for high schools.* M.: “Science”, 1992, 536 p.

5. WU Ze-Qing, PANG Jin-Qiao, HAN Guo-Xing, YAN Jun Ionization Balance in Non-Local-Thermodynamic-Equilibrium Plasmas // *Chinese Physical Society and IOP Publishing Ltd*. 2004, p. 877-880.

6. V. Boretskij, A. Veklich, Y. Cressault, A. Gleizes, Ph. Teulet. Non-equilibrium plasma properties of electric arc discharge in air between copper electrodes *// Problems of Atomic Science and Technology. Series “Plasma Physics” (18).* 2012, № 6, p. 181-183.

7. A. Veklich, A. Lebid. Technique of electric arc discharge plasma diagnostic: peculiarities of registration and treatment of spectra // *Bulletin of Taras Shevchenko National University of Kyiv. Series “Radiophysics and Electronics”*. 2012, № 18, p. 6 -9.

8. A. Veklich, M. Kleshich, S. Fesenko, V. Boretskij, Y. Cressault, Ph. Teulet. Investigation of electric arc discharge plasma between one-component Cu and Ni and composite Ag-Ni electrodes // *Problems of Atomic Science and Technology. Series “Plasma Physics.*” 2017, v. 107, № 1, p. 171-174.

9. V.F. Boretskij, Y. Cressault, Ph. Teulet, A.N. Veklich. Plasma of electric arc discharge in carbon dioxide with copper vapours // *XIX th Symposium on Physics of Switching Arc (FSO 2011). Brno, Czech Republic. September, 5-9.* 2011, p. 121-124.

10. A. Veklich, S. Fesenko, V. Boretskij, Y. Cressault, A. Gleizes, Ph. Teulet, Y. Bondarenko, L. Kryachko. Thermal plasma of electric arc discharge in air between composite Cu–C electrodes // *Problems of Atomic Science and Technology. Series “Plasma Physics” (20).* 2014, № 6, p. 226-229.

11. A.N. Veklich, S.O. Fesenko, V.F. Boretskij, M.M. Kleshich. Measuring of the electric field of a positive column in arc discharges // *XI International Scientific Conference “Electronics and Applied Physics”. Taras Shevchenko National University of Kiev. Faculty of Radio Physics and Computer Systems. Kyiv, Ukraine. October, 21-24.* 2015, p. 149-150.

12. J. Richter. *Plasma Diagnostics /* Edited by W. Lochte-Holtgreven. North-Holland: “Publishing Company”, 1968, 932 p.

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ИССЛЕДОВАНИЕ НЕРАВНОВЕСНОСТИ В ПЛАЗМЕ ЭЛЕКТРОДУГОВОГО РАЗРЯДА МЕЖДУ ПЛАВЯЩИМИСЯ ЭЛЕКТРОДАМИ

С.А. Фесенко, М.М. Клешич, А.Н. Веклич

Рассматриваются разные сценарии обработки экспериментальных данных, которые могут привести к противоположным выводам о возможности реализации в плазме локального термодинамического равновесия. В частности, степень детализации компонент в плазме свободногорящей в воздухе электрической дуги (а именно, учет молекулы окиси азота), влияет на достоверность определения границы области неравновесности в плазме электродугового разряда силой тока 3,5 А.

ДОСЛІДЖЕННЯ НЕРІВНОВАЖНОСТІ В ПЛАЗМІ ЕЛЕКТРОДУГОВОГО РОЗРЯДУ МІЖ ПЛАВКИМИ ЕЛЕКТРОДАМИ

С.О. Фесенко, М.М. Клешич, А.М. Веклич

Розглядаються різні сценарії обробки експериментальних даних, які можуть призвести до протилежних висновків щодо можливості реалізації в плазмі локальної термодинамічної рівноваги. Зокрема, ступінь деталізації компонент у плазмі, вільноіснуючої в повітрі електричної дуги (а саме, врахування молекули окису азоту), впливає на достовірність визначення межі області нерівноважності в плазмі електродугового розряду силою струму 3,5 А.