doi:10.14311/ppt.2024.3.61
Plasma Physics and Technology **11**(3):61–66, 2024

OPTICAL EMISSION SPECTROSCOPY OF BREAKING ARC PLASMA BETWEEN CONSUMABLE ELECTRODES

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Abstract. The investigation focuses on the optical emission spectroscopy of plasma generated by breaking arc between single-component Cu and composite Cu-W electrodes manufactured using shock sintering technology at temperature of 750°C. The electrodes were subjected to arc currents of 4, 50, and 104 A. Optical emission spectroscopy with high spectral and temporal resolution was employed to investigate the plasma with copper and tungsten vapour admixtures. The temporal evolution of temperature in the plasma was determined by the Boltzmann plot technique based on the emission intensities of Cu I spectral lines. Temporal evolution of electron densities were determined from the full width at half maximum of Cu I 515.3 nm spectral line. These initial plasma parameters integrated over the volume of breaking arc were utilized to calculate the temporal evolution of plasma compositions and contents of metal vapours admixtures in discharge gap.

Keywords: Breaking arc, optical emission spectroscopy, copper-tungsten composite materials, temporal evolution.

1. Introduction

Reliability of switching electrical devices (hereinafter referred to as switches) is one of the essential factors ensuring the efficiency of the electrical network. Switches are divided into classes based on their intended purpose, the value of switched power, and each class has its structural features. All switches have a common issue, which is the erosion of contacts due to an electric arc that occurs when an electric circuit is switched. Despite significant success in increasing the resistance of contact materials to arc erosion, the composition and manufacturing technology of such materials are not yet perfect, necessitating further research.

Composite materials, particularly copper-tungsten composites, have garnered significant interest owing to their superior mechanical and thermal properties in comparison to conventional electrode materials. These composites offer a unique blend of advantages, including high electrical conductivity, refractoriness, and exceptional erosion resistance. Notably, these properties are attributed to the absence of chemical interaction between metals in both the solid and liquid phases. As a result, copper-tungsten composites have emerged as promising candidates for various applications requiring robust and reliable electrode materials.

In recent years, Cu-W composite materials have garnered significant attention in material science investigation. For instance, in the study by Cui et al. [1], two distinct modes of surface erosion in W70Cu30 composites were identified: one characterized by evaporation predominance and the other by splashing. The transition in erosion behavior of the W70Cu30 anode is primarily governed by the melting temperature of tungsten. Upon reaching this temperature, droplet ejections become the dominant mechanism driving the erosion behaviour.

In the study [2], the arc erosion behaviour of Cu-W material in a circuit breaker model was experimentally examined. Utilizing a pyroscope, the authors determined the average surface temperature of the contact material. Their investigation revealed the presence of two distinct types of arc erosion processes, each resulting in significant alterations to the contact surface structure and the electrode material following repeated arc erosion.

In the work [3], G-Cu-W and Cu-W contact samples were examined during arcing tests conducted under a 5 kA peak current. Experimental results indicated that the inclusion of graphene led to a reduction in damage to the contact surface and a decrease in surface roughness of the Cu-W matrix following the arcing tests.

The aim of this work is to investigate the temporal behaviour of metal vapour admixtures in the plasma of breaking arcs between Cu-W composite electrodes. Additionally, the results obtained from determining the plasma parameters are compared with those determined in the plasma of breaking arcs between single-component copper electrodes.

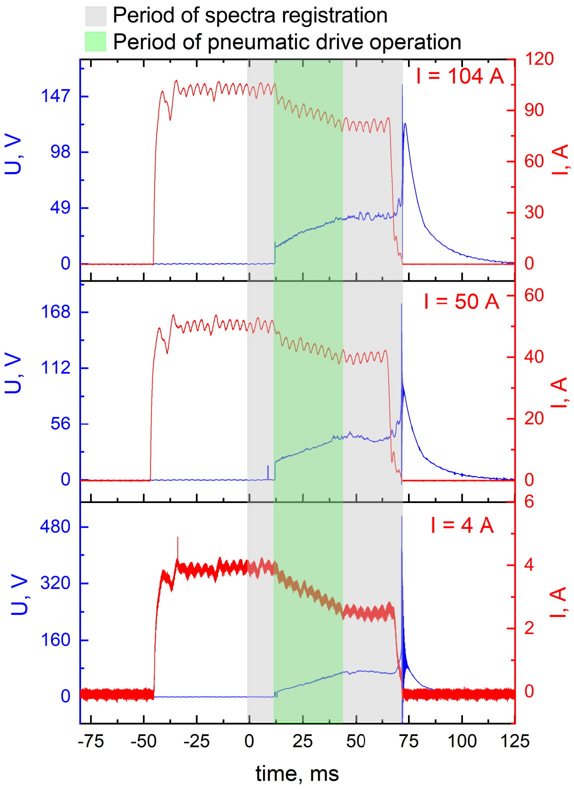

Figure 1. Oscillograms of voltages and currents of electric arc discharges between composite Cu-W electrodes

2. Experimental Investigation

Experiments were carried out in High Current Laboratory at Brno University of Technology (BUT), Czech Republic. The main target of the facility is high power experimentation in developing and testing of a wide range of switching devices.

The electrode assembly comprised the upper fixed holder of the cathode electrode and another moving holder for the anode electrode, operated by a pneumatic drive. The pneumatic drive made it possible to initiate a breaking arc by moving the electrodes from the closed state to a distance of 10 mm in 31.5 ms. Prior to each test, the electrodes were short-circuited. An activation of the pneumatic drive occurred approximately 60 ms after the start of the experiment, marking the initiation of the arc burning process in the discharge gap. Throughout the entire arcing period, emission spectra of the plasma were continuously registered. For further details on the electrical scheme of the experimental setup, refer to the previous work [4]. Typical oscillograms of voltage and current with marked periods of spectra registration and pneumatic drive operation are shown in Figure 1

The primary focus of this study is the investigation of the optical emission of plasma generated by electric arc discharge between composite Cu-W electrodes. These electrodes were composed of Cu-W materials with a mass ratio of 30/70%, manufactured at the Frantsevich Institute for Problems of Materials Science, NAS of Ukraine, using shock sintering technology at 750°C [5]. The electrodes possessed a square cross-section measuring 5×5 mm. The investigations were conducted at arc currents of 4, 50, and 104 A in air atmosphere of 1 bar.

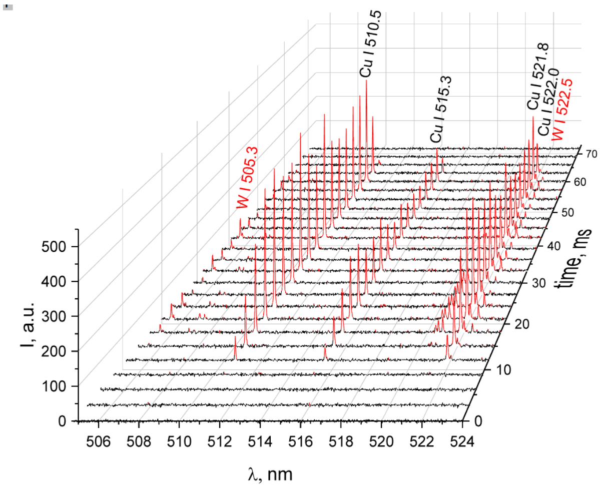

Figure 2. Typical temporal evolution of emission spectra registered in plasma of breaking arc discharge between Cu-W composite electrodes at current of 104 A

In addition, breaking arcs were initiated between single-component Cu electrodes to provide further clarification of the obtained results. These electrodes had the same square cross-section dimensions as the composite Cu-W electrodes.

The emission spectra of the plasma were captured using an optical fiber with 600 μm diameter. The fiber was installed at a distance of approximately 1.5 m from the arc, which made it possible to record the entire discharge. High-resolution spectrograph, the Andor Shamrock 500i, equipped with a diffraction grating of 1200 l/mm, a blaze of 500 nm and a narrow spectral range of 40 nm [6] was used. Newton DU940P-BU CCD camera was used as a registration device [7]. The full width at half maximum (FWHM) of the instrumental function was determined using the Hg-Ar calibration source and found to be 0.045 nm (width of entrance slit was 15 μm). Each experiment involved the recording of 25 spectra, with an exposure time of 2.68 ms and a shift after exposition of 0.32 ms. It is worth noting that the noticeable emission of spectral lines was registered starting from approximately the 12th millisecond, depending on the discharge. The reason is that the registration of spectra began earlier than the activation of the pneumatic drive.

Each of the 25 spectra obtained in each experiment underwent meticulous processing to identify spectral lines associated with copper and/or tungsten. For this study, the spectrometer was specifically tuned to a wavelength of 525 nm, providing a spectral measurement range from 505 to 545 nm. Typical temporal evolution of emission spectra registered in plasma of breaking arc discharge between Cu-W composite electrodes at current of 104 A is shown in Figure 2.

The Boltzmann plot technique [8] based on the emission intensity of Cu I 510.5, 515.3, and 521.8 nm

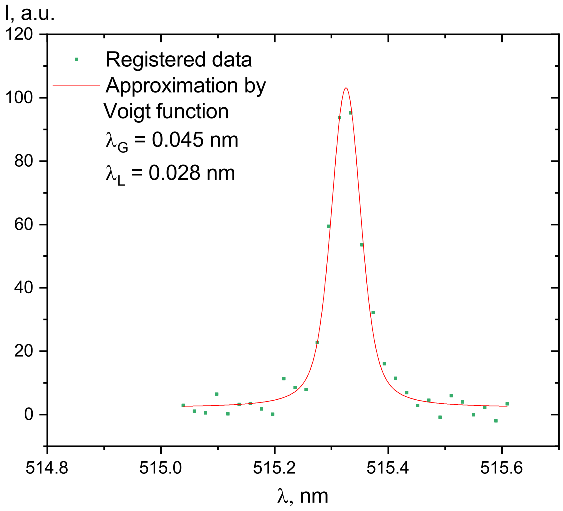

Figure 3. Typical profile of Cu I 515.3 spectral line and its approximation by Voigt function. The profile was registered at 45th millisecond of arc burning between composite Cu-W electrodes at current of 4 A

spectral lines were used to determine the temperature integrated over the volume of breaking arc plasma. Since this does not provide spatial resolution, therefore, it is appropriate to use the term of the so-called distribution temperature. W I 505.3 and 522.5 nm spectral lines were identified in this spectral range as well. However the temperature was not determined using them due to the non-substantial difference (∼0.31 eV) in the energies of their upper levels, which would result in significant error values.

The FWHM of Cu I 515.3 nm spectral line was utilized to determine the temporal evolution of the electron density in the discharge gap. The spectral profile of the line was approximated using a Voigt function to deconvolute the influence of the instrumental function and obtain the Lorentzian component of the function. This Lorentzian width was considered as the Stark width of the line, assuming that the Quadratic Stark effect is the dominant broadening mechanism for the line. In that case, the electron density can be calculated as follows:

$$N_e = K \cdot \Delta\lambda, \tag{1}$$

where K – Stark broadening parameter which defines electron density normalized by a line FWHM, Δλ – FWHM of a spectral line. The Stark Broadening parameter for Cu I 515.3 nm spectral lines is taken from [9] and equal 0.346. Typical profile of Cu I 515.3 spectral line as well as its approximation by Voigt function is shown in Figure 3.

The plasma parameters obtained, namely electron density and distribution temperature, were utilized to calculate the plasma composition and subsequently determine the content of metal vapour admixtures in the discharge gap. This calculation was performed using the system of equations presented in [10]. It can be assumed that local thermodynamic equilibrium (LTE) is realized in such a plasma [8, 11], allowing the distribution temperature to be considered as the plasma temperature.

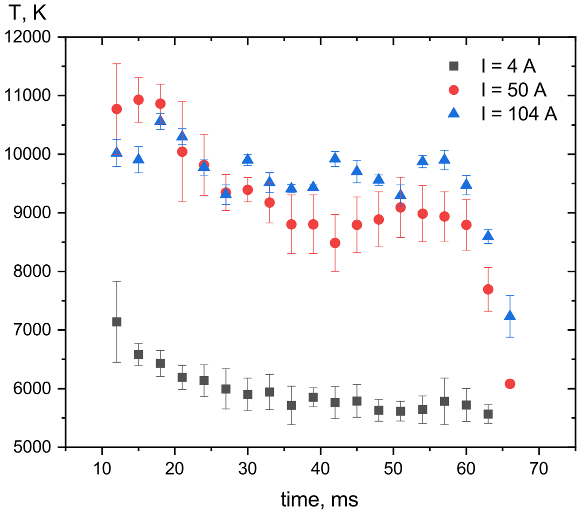

Figure 4. Temporal evolution of distribution temperatures in the plasma of arc discharge between composite Cu-W electrodes at currents of 4, 50 and 104 A

3. Results and Discussions

The temporal evolution of the distribution temperatures obtained by Boltzmann plot technique in the plasma of electric arc discharge between Cu-W composite electrodes at current of 4, 50 and 104 A are shown in Figure 4. The electron densities obtained from FWHM of Cu I 515.3 nm spectral line (see Figure 5) at the same discharge conditions are shown in Figure 6.

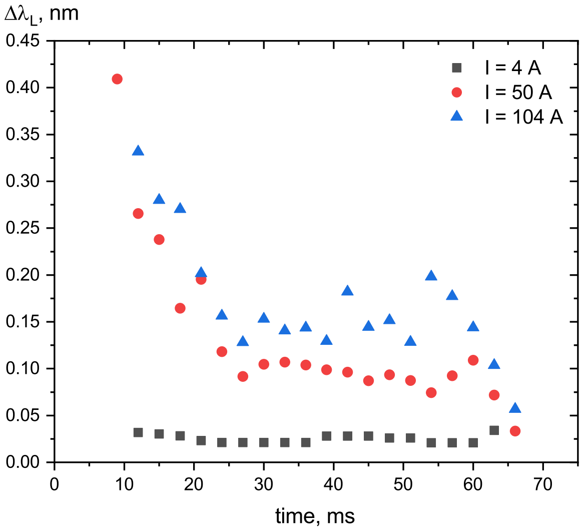

Figure 5. Temporal evolution of the widths of Cu I 515.3 nm spectral lines in the plasma of arc discharge between composite Cu-W electrodes at currents of 4, 50 and 104 A

One can see that neither distribution temperature nor electron density do not undergo significant changes when the arc current increases from 50 to 104 A. However, a significant increase in both this parameters is

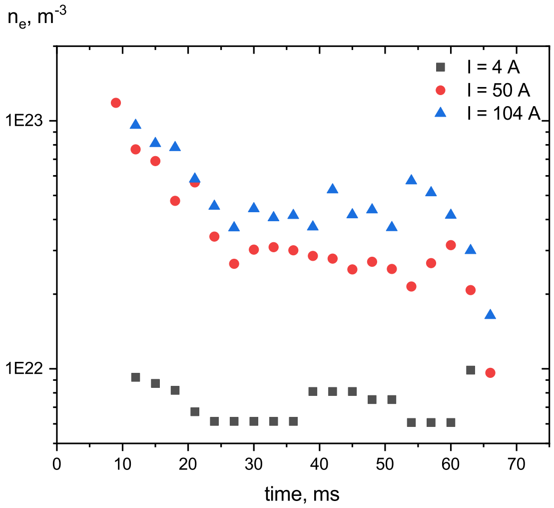

Figure 6. Temporal evolution of electron densities in the plasma of arc discharge between composite Cu-W electrodes at currents of 4, 50 and 104 A

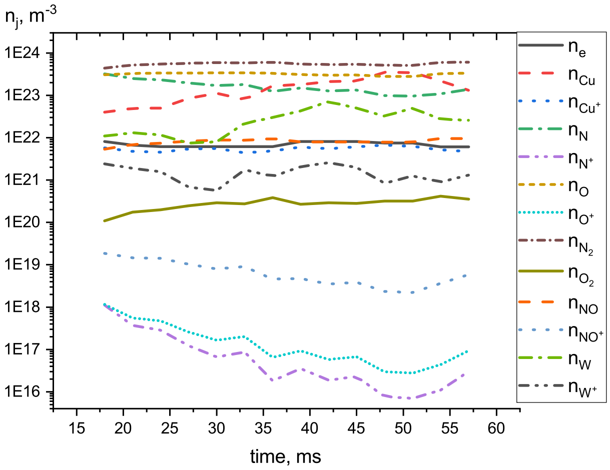

Figure 7. Temporal evolution of plasma composition of arc discharge between composite Cu-W electrodes at current of 4 A

observed when the current increases from 4 to 50 A. It should be also noted that the values of the electron density in the breaking arc of 4 A differs significantly from those obtained in a quasi-stationary DC arc at a current of 3.5 A. This difference may be due to the fact that studies of a quasi-stationary arc were carried out using spatial resolution in the midsection of the arc discharge [8]. In turn, these studies recorded all plasma radiation that is captured by the optical fiber aperture. Thus, the consideration could include emission not only from the positive plasma column, but also from near-electrode areas, in which the electron density is higher. The inhomogeneity of the plasma was not taken into account.

The temporal evolution of the plasma composition in arc discharge at currents of 4 A calculated basing on the obtained evolution of electron densities and distribution temperature under LTE assumption are shown in Figure 7. The evolution of content of copper and tungsten vapour admixtures are shown in Figure 8

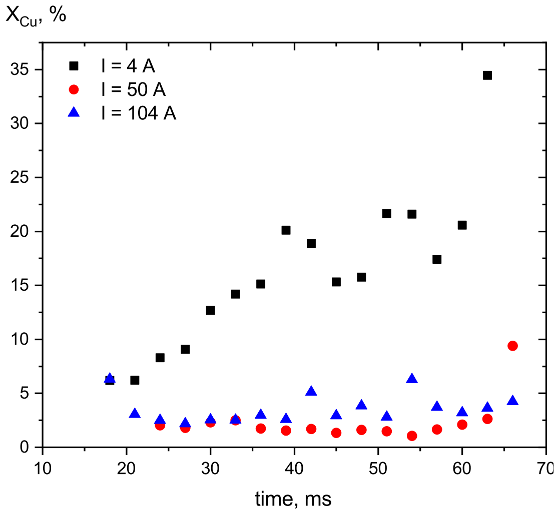

Figure 8. Temporal evolution of contents of copper vapour admixtures in the plasma of arc discharge between composite Cu-W electrodes at currents of 4, 50 and 104 A

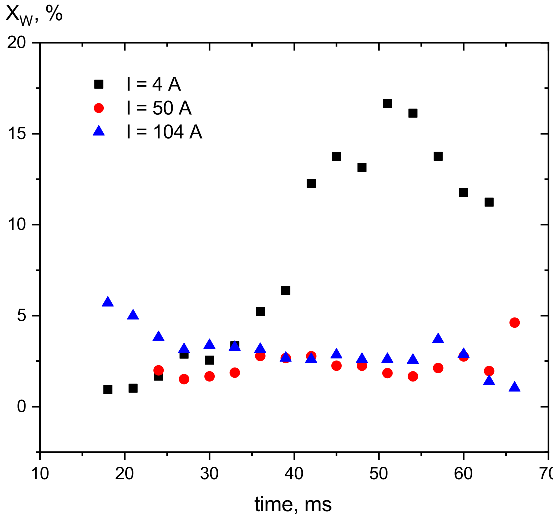

Figure 9. Temporal evolution of contents of tungsten vapour admixtures in the plasma of arc discharge between composite Cu-W electrodes at currents of 4, 50 and 104 A

and 9, respectively.

As one can see from Figure 7 for an arc at the current of 4 A, the plasma-forming gas is predominantly composed of nitrogen and oxygen molecules. Furthermore, with an increase in the current and consequently, the temperature of the plasma, the molecules dissociate, and the plasma-forming gas primarily consists of nitrogen and oxygen atoms. The conductivity of the arc plasma at 4 A is primarily attributed to the ionization of metal atoms. As the current increases, the ionization of nitrogen and oxygen atoms becomes more noticeable, while NO molecules do not significantly contribute to the arc plasma at 4 A, nor at 50 A, and 100 A.

From the analysis of the metal vapour admixtures in the plasma (see Figure 8 and 9), it is evident that the total content of copper and tungsten in discharges

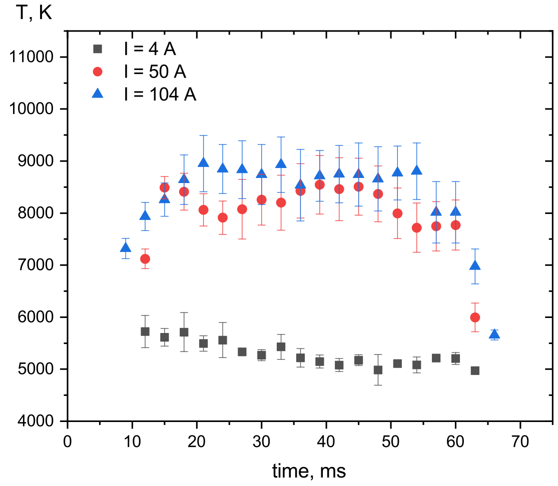

Figure 10. Temporal evolution of distribution temperatures in the plasma of arc discharge between single-component Cu electrodes at currents of 4, 50 and 104 A

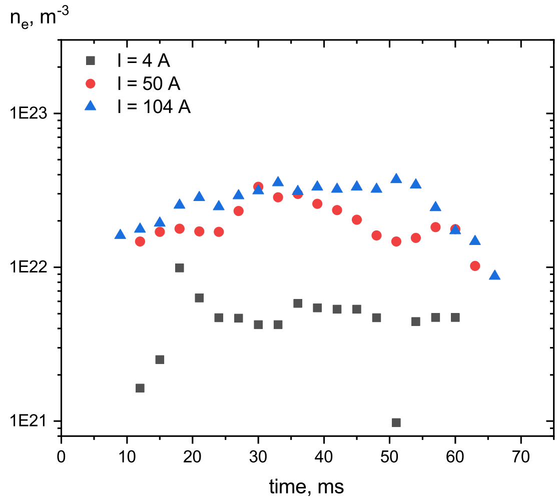

Figure 11. Temporal evolution of electron densities in the plasma of arc discharge between single-component Cu electrodes at currents of 4, 50 and 104 A

at the current of both 50 A and 104 A does not exceed 10%. However, in the plasma of an electric arc discharge with a current of 4 A, particularly at certain time intervals, the total content of metals can reach 25-35%, which is unusually high for low-current arcs.

It can be assumed that in the plasma of an breaking arc at the current of 4 A, LTE is not realized, and therefore, the distribution temperature determined by the Boltzmann plot technique may not be considered as the plasma temperature. This is due to the combination of high electron concentrations and relatively low temperatures. The LTE model, upon which the system of equations for calculating the composition of the plasma is based, is typically justified only at very high metal concentrations.

To validate this hypothesis, analogous plasma investigations of breaking arcs were carried out at the currents of 4, 50, and 104 A between single-component copper electrodes. Figure 10 and 11 depict the time evolution of distribution temperatures and electron densities in the plasma of arcs between single-component copper electrodes, respectively. It is observed that the behaviour of these parameters with increasing arc current mirrors that of the plasma in arc discharges between composite electrodes.

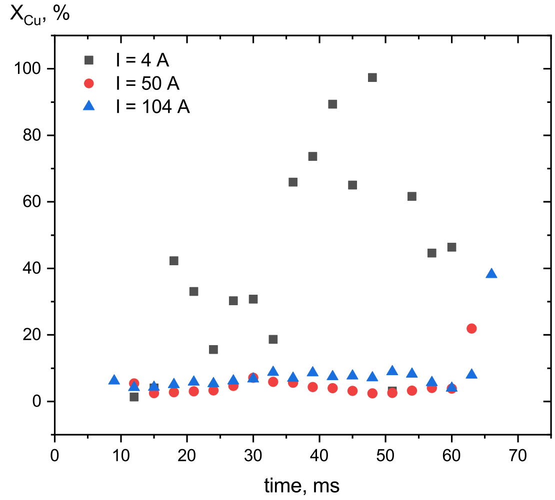

Figure 12. Temporal evolution of contents of copper vapour admixtures in the plasma of arc discharge between single-component Cu electrodes at currents of 4, 50 and 104 A

The temporal evolution of the compositions of copper vapour admixtures in the plasma of breaking arcs at given current values are presented in Figure 12.

The results of composition calculations at specific time intervals (see Fig.12) indicate that the content of copper vapour admixtures in the plasma of an arc discharge at the current of 4 A can reach 90–99%, suggesting that the plasma primarily consists of metal vapours. Such behaviour of the electrode components in the plasma of low-current arc discharges is considered anomalous based on a broad range of previous studies [10, 12].

This implies that the LTE model, upon which the calculations are predicated, will only hold for such electron densities and plasma temperatures if the plasma-forming gas comprises solely atoms of electrode origin, which seems unlikely. Consequently, we can infer that the local thermodynamic equilibrium is not realized in the plasma of breaking arcs at the current of 4 A. Possible reasons may be the influence of the plasma's own radiation [13, 14] and nonequilibrium ionization in the near-electrode regions of the arc.

It should be noted that the obtained results are estimates. Not considering the plasma inhomogeneity, as well as registration of emission spectra both from the positive arc column and from the near-electrode regions leads to significant inaccuracies in calculations of the plasma composition. Thus, the obtained results cannot be considered absolutely correct, nevertheless, they are very useful for assessing the plasma state and the realization of local thermodynamic equilibrium.

4. Conclusions

The investigation of the optical emission of plasma in breaking arc between composite Cu-W electrodes has provided valuable insights into the behaviour of plasma under varying conditions. Analysis of emission spectra revealed significant differences in plasma composition and behaviour with changes in arc current. It has been found that local thermodynamic equilibrium was not achieved in the plasma of breaking arcs at the current of 4 A, as evidenced by the anomalous behaviour of the obtained results of metal vapours admixtures calculations. These observations underscore the complexity of plasma dynamics and the challenges associated with achieving LTE in low-current arc discharges. Moving forward, further investigation is warranted to explore the underlying mechanisms driving these phenomena and to refine our understanding of plasma behaviour in electric arc discharges.

5. Acknowledgments

This research work has been carried out in the Centre for Research and Utilization of Renewable Energy (CVVOZE). Authors gratefully acknowledge financial support from the Ministry of Education, Youth and Sports under institutional support.

Some of the authors partially carried out the investigations within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement № 101052200–EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

The authors consider it their pleasant duty to express their gratitude to Prof. Veklich and Dr. Boretskij for essential help in organizing and conducting experimental studies and useful advice during the preparation of this article for publication.

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