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INVESTIGATION OF SPATIAL DISTRIBUTION OF METAL VAPOURS ADMIXTURES IN THE PLASMA OF AN ELECTRIC ARC DISCHARGE

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This work focuses on diagnosing the plasma in an electric arc discharge in an argon flow using optical emission spectroscopy. The method employed for determining the population of energy levels and the concentration of metal atoms based on the absolute values of emission intensity is described and validated. The experimental setup includes a spectrograph and an RGB CMOS matrix as the emission registration device. By obtaining the absolute values of the spectral radiances of Cu I lines and considering the axial symmetry of the electric arc discharge, the local radiation intensity of these lines is determined. Radial distributions of copper atom concentrations are then calculated using the absolute values of emission intensities and the radial distribution of the excitation temperature, which is determined using the Boltzmann plots technique. Two methods are employed for calculating the atom concentrations. The first method involves Boltzmann plots based on four spectral lines of Cu I and the corresponding excitation temperature. The second method determines the concentrations directly from the population of copper's energy levels, which are derived from the absolute values of emission intensity of the Cu I spectral lines. The results obtained from these two methods exhibit a coincidence of within 20%, supporting the recommendation of this technique for plasma diagnostics in electric arc discharges.

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INTRODUCTION

The study of electric arc discharge plasma with metal vapour admixtures is of great interest to researchers due to its scientific significance and numerous practical applications. Processes such as electric arc welding and cutting [1 - 3], plasma surface treatment [4 - 7], and current switching in electrical devices [8] involve the evapouration of materials from switching contacts and electrodes. To address the challenges posed by these applications, the development of diagnostic methods for electric arc discharge plasma with metal vapour admixtures is crucial.

During the switching of an electric circuit, arc discharge occurs, leading to contact erosion [8] and reducing the service life of switches and contacts. Therefore, investigating the physical processes that occur in plasma media during switching and on contact surfaces is of great importance. The study of electric arc discharge plasma with metal vapour admixtures from electrode materials can contribute to reducing electrode erosion by optimizing material composition and developing new manufacturing technologies.

Traditionally, the erosion intensity of electrode materials caused by the thermal effect of electric arc discharge plasma is indirectly determined by calculating the content of metal vapours in the positive plasma column based on its equilibrium composition [9, 10]. This method requires experimental determination of plasma parameters such as temperature and electron density. The most common approach for obtaining electron density is direct calculation from the full width at half-maximum (FWHM) of the spectral line contours [11]. However, this approach has limitations in practical diagnostics. It relies on high-resolution spectral devices to accurately observe emission spectral line contours, especially in low-current electric arc discharges. Moreover, the width of spectral line contours in such plasma sources can be comparable to the instrumental function of spectral devices.

The main objective of this work is to propose an alternative parameter to electron density for calculating the equilibrium plasma composition and to develop a method for its determination. Specifically, the method focuses on measuring the concentration of metal vapour admixtures in the discharge gap using the absolute values of emission intensity.

1. DETERMINATION OF THE ATOMS' CONCENTRATION BY THE METHOD OF ABSOLUTE INTENSITIES OF SPECTRAL LINES

The emission intensity (or emissivity) of a spectral line should be considered as the energy emitted in 1 s in 1 m^3 within the contour of the spectral line [12]. Then the total emissivity of the spectral line ε_L can be expressed by eq. (1):

$$\varepsilon_L = \int\limits_{Line} \varepsilon_{\lambda,L} d\lambda = \frac{hc}{4\pi\lambda} A_{ki} n_k , \qquad (1)$$

where $\varepsilon_{\lambda,L}$ is the spectral distribution of the emissivity of the spectral line; h is the Planck constant; c is the speed of light; λ is the wavelength in the centre of the spectral line; A_{ki} is the probability of the electron transition from the k^{th} to the i^{th} energy level (the Einstein coefficient for spontaneous emission); n_k is the concentration of emitting particles or the population of the k^{th} level.

Since the absolute values of the total emissivity of the spectral line were determined, it is possible to calculate the population of the k^{th} energy level by eq. (2):

$$n_k = \varepsilon_L \frac{4\pi\lambda}{hcA_{ki}} . \qquad (2)$$

According to the Boltzmann law:

$$n_k = \frac{g_k}{\Sigma_a} n e^{-\frac{E_k}{k_B T}} , \qquad (3)$$

where g_k is the statistical weight of the k^{th} energy level; Σ_a is the partition function of atoms of the emitting ma-

terial; E_k is the energy of the k^{th} level; k_B is the Boltzmann constant, and T is the excitation temperature. Taking into account eq. (3) in (1), the intensity dependence on the temperature and on the concentration of atoms of the emitting element n is defined by eq. (4):

$$\varepsilon_L = \frac{hc}{4\pi\lambda}\frac{A_{ki}g_k}{\Sigma_a} n e^{-\frac{E_k}{k_B T}}. \quad (4)$$

In case of a known oscillator strength f_{ik}, the transition probability A_{ki} can be determined by eq. (5):

$$A_{ki} = \frac{8\pi^2 e^2}{m_e c\lambda^2}\frac{g_i}{g_k} f_{ik}. \quad (5)$$

The linearization of (4) leads to equation (6) of a slope-intercept form $y = ax + b$:

$$\ln\left(\frac{\varepsilon_L \lambda}{A_{ki} g_k}\right) = -\frac{E_k}{k_B T} + \ln\left(\frac{hc}{4\pi}\frac{n}{\Sigma_a}\right), \quad (6)$$

where $y = \ln\left(\frac{\varepsilon_L\lambda}{A_{ki}g_k}\right); x = E_k; a = -\frac{1}{k_B T}; b = \ln\left(\frac{hc}{4\pi}\frac{n}{\Sigma_a}\right)$.

Using the Boltzmann plot technique based on the intensities of at least two spectral lines, the excitation temperature T can be determined by eq. (7):

$$T = -\frac{1}{k_B a}. \quad (7)$$

Obtaining the temperature parameter allows determining the partition function of atoms using eq. (8) due to the latter dependence on the former:

$$\Sigma_a = \sum_m g_m e^{-\frac{E_m}{k_B T}}. \quad (8)$$

Based on this, it is possible to calculate the concentration of particles of the emitting element according to eq. (9):

$$n = \frac{e^b 4\pi\Sigma_a}{hc}. \quad (9)$$

Thus, it is enough to determine the absolute values of the spectral lines intensity to obtain the population of energy levels and the atoms' concentration of an emitting element.

2. DETERMINATION OF ABSOLUTE VALUES OF THE EMISSION INTENSITY OF SPECTRAL LINES

The intensity ε_L can be determined from the radiance of spectral lines, which is obtained experimentally. The radiance should be understood as the energy that passes through a unit of area per unit of time within a unit solid angle perpendicular to the selected plane.

For an isotropic, optically thin and homogeneous plasma, the emissivity of the spectral line $\varepsilon_{\lambda,L}$ depends on its radiance I_L as $\varepsilon_L = I_L/d$, where d is the width of the emitting layer [12].

In the case of optically thin and inhomogeneous plasma, but which is characterized by cylindrical symmetry (e.g. the plasma of the electric arc discharge), the dependence takes the form:

$$\varepsilon(r) = -\frac{1}{\pi}\int_r^{r_0} \frac{I(x)dx}{\left(x^2 - r^2\right)^{1/2}}, \quad (10)$$

where $\varepsilon(r)$ is the emission intensity at a distance r from the axis of symmetry of the radiation source (radial distribution of the emissivity); r_0 is the emission boundary; $I(x)$ is the radiance integrated along the line-of-sight at a distance x from the centre of the radiation source (spatial distribution of the radiance). An integral equation of the type (10) is known as the Abel integral. Its numerical solution was proposed by Bockasten [13], which makes it possible to determine the values of the emission intensity (local values) of spectral lines at known values of their radiance (observed values).

Thus, to determine the absolute values of the intensity of spectral lines in the plasma of electric arc discharges with cylindrical symmetry, it is necessary to determine the absolute values of the radiance of these spectral lines.

The observed radiance values I_λ^{obs}, obtained using the spectral device, differ from the radiance values I_λ^* of the emission that falls on the sensor (for example, a CMOS matrix), as follows:

$$I_\lambda^* t = \frac{I_\lambda^{obs}}{\chi_\lambda^*}, \quad (11)$$

where t is the registration time (exposure of the CMOS matrix), and χ_λ^* is the spectral sensitivity of the sensor.

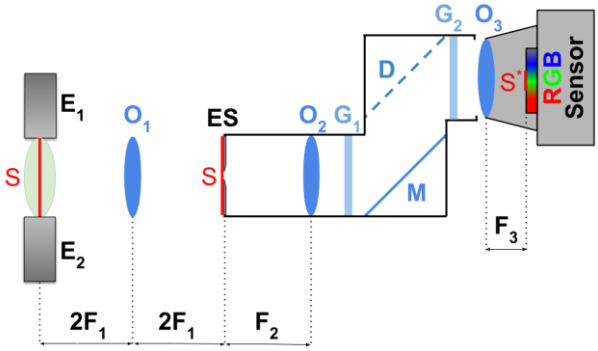

Fig. 1. Optical scheme of the experimental setup for studying emission with spatial resolution

The issue of determining the absolute values of emission intensity is reduced to determining the spectral sensitivity of the used spectral device, which is calibrated in energy units (W·m^2/nm according to spectral radiance units).

In order to solve this issue, a spectrograph based on a diffraction grating with a period of 600 l/mm has been used (Fig. 1). The lens O^1 was installed between the radiation source S and the horizontally oriented entrance slit ES of the spectrograph (slit height 20 μm) at a double focus distance (F_1 = 200 mm) from each. Thus, an image was formed at the ES without magnification, and the fulfillment of the Abbe sine condition [12] ensured the equality of the emission intensity value directly from the source and its image (radiation losses depend only on the transmittance of the O_1).

In turn, the ES is located in the focus F_2 of the O_2 collimator. A parallel beam of light formed by the lens O_2 and directed through the glass window G_1 is reflected from the mirror M and enters the diffraction grating D. The radiation that passes through the window G_2 is focused by the lens O_3 to obtain an image S^* on the surface of the detector. In this work, the CMOS matrix

(RGB Sensor) of the Nikon D7000 camera was used as a light-sensitive element.

If the spectral radiance of the radiation source is denoted as I_λ, then with this configuration of the optical scheme, the spectral radiance that gets to the sensor can be expressed as:

$$I_\lambda^* = I_\lambda \Omega \mathrm{T}, \quad (12)$$

where Ω is the solid angle at which the dispersing element D is seen from the entrance slit ES; τ is the total transmittance of the optical scheme, which includes the transmittances of the lenses O_1 and O_3, the windows G_1 and G_2, the collimator O_2 and all other possible losses. Then, taking into account eq. (12) in (11), the equation (13) can be obtained:

$$I_\lambda = \frac{I_\lambda^{obs}}{\chi_\lambda^* \Omega \mathrm{T} t}, \quad (13)$$

where χ_λ is the spectral sensitivity of the proposed spectral device:

$$\chi_\lambda = \chi_\lambda^* \Omega \mathrm{T} = \frac{I_\lambda^{obs}}{I_\lambda t}. \quad (14)$$

The spectral radiance I_λ can be calculated theoretically and registered using a reference source of emission. A tungsten band-lamp of the СИ-8-300 [14] type with an incandescent band has been used as a source of reference emission. Taking into account the temperature of tungsten, the spectral radiance emitted by band of such a lamp, can be calculated as:

$$I_\lambda = I_{\lambda,T} = B_{\lambda,T} \tau_\lambda \varepsilon_{\lambda,T}, \quad (15)$$

where τ_λ is the transmittance of the lamp window, $\varepsilon_{\lambda,T}$ is the emissivity of tungsten as a real "gray body" at temperature T, $B_{\lambda,T}$ is the spectral radiance of a blackbody at a true temperature T. According to Planck's law:

$$B_{\lambda,T}\left[\frac{W}{m^2 nm}\right] = \frac{2hc^2}{\lambda^5}\left(e^{\frac{hc}{\lambda k_B T}} - 1\right)^{-1}. \quad (16)$$

Since the tungsten incandescent band is not a blackbody, the calibration of the reference lamp (usually by the method of optical pyrometry) is carried out according to its brightness temperature T_{br}. The brightness temperature of the body corresponds to the temperature of the blackbody, at which its spectral radiance at a wavelength of 650 nm is equal to the radiance of a body with a true temperature at the same wavelength. The true temperature T is related to the brightness temperature T_{br} by eq. (17):

$$T = \frac{hcT_{br}}{k_B T_{br} \ln\left[\tau_0 \varepsilon_T\right] + hc} \quad (17)$$

or

$$T = \left(1.041 \cdot 10^{-4} \lg\left(\tau_0 \varepsilon_{0,T}\right) + \frac{1}{T_{br}}\right)^{-1}. \quad (18)$$

In eq. (17) and (18) τ_0 is the transmittance of the lamp window at a wavelength of 650 nm, and $\varepsilon_{0,T}$ is the emissivity of tungsten at the temperature T at the same wavelength.

The calibration curve of the reference tungsten band-lamp (the dependence of T_{br} on the incandescent current I) is shown in Fig. 2. In this work, the current was 21.7 A, which corresponds to the brightness temperature of 2175 K. The temperature of tungsten, calculated from eq. (18), is 2400 K. The spectral distributions of the transmittance and emissivity of tungsten at a temperature of 2400 K are shown in Figs. 3 and 4, respectively.

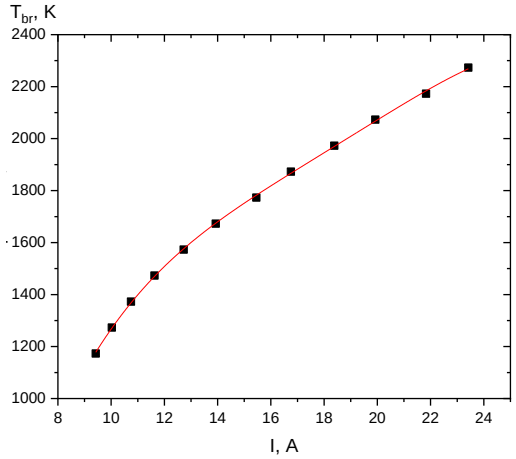

Fig. 2. Calibration curve of a reference tungsten lamp with an incandescent band

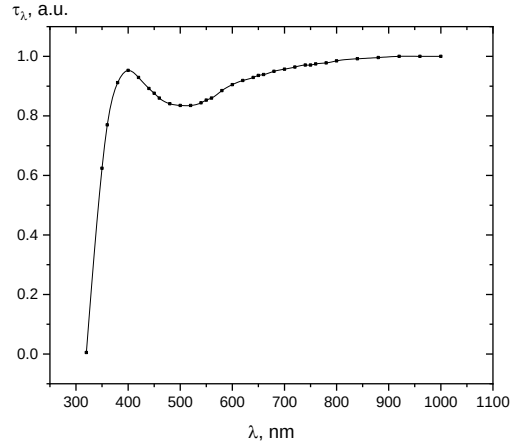

Fig. 3. Spectral distribution of the transmittance of glass [14]

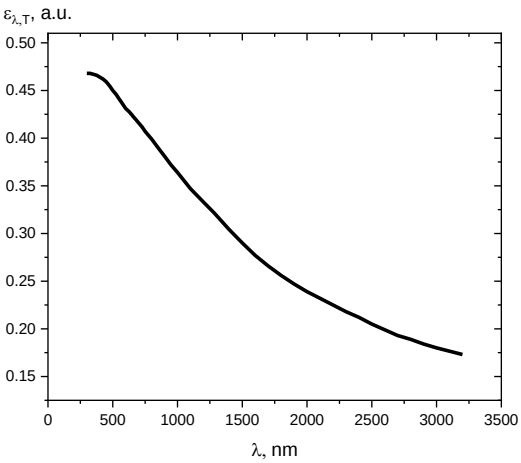

Fig. 4. Emissivity of tungsten at a temperature of 2400 K [15]

Since an image sensor of the digital camera is used as a detector, the obtained images of emission spectra require additional processing. Namely, images obtained in *. NEF format (without compression and digital processing) with a resolution of 6036×4020 pixels and a colour depth of 12 bits were linearized from the distribution of tetrads of colour filters array (Bayer's filters) to the distribution of pixels with RGB components.

Then the RGB images were converted to grayscale for their subsequent calibration both in wavelength and in spatial coordinates.

The plasma emission spectrum of the electric arc discharge between single-component copper and nickel electrodes has been obtained and applied to calibrate the spectral coordinate of the registration device (Fig. 5). The choice of electrodes is due to the fact that the spectrum of copper is well studied, and the spectrum of nickel contains a large number of spectral lines that can be used as reference points for wavelength calibration. Wavelength data for Cu I and Ni I spectral lines were taken from the NIST database [16].

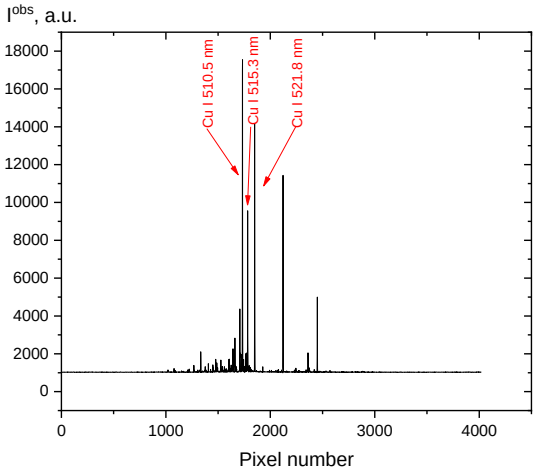

Fig. 5. Observed emission spectrum of arc discharge plasma between Cu and Ni electrodes according to pixel number

At the first iteration of the calibration of the spectral dependence, the lines of copper Cu I 510.5, 515.3, and 521.8 nm have been identified and linear interpolation of wavelength values has been performed. The dependence of the wavelength on the pixel number obtained in this way is not sufficiently accurate, since the dispersion of the diffraction grating is non-linear. Therefore, in the next iteration, the positions of all reference wavelengths have been determined, the values of which were taken from the NIST database (see Fig. 6). The calibration curve has been obtained by interpolating the wavelengths by a second degree polynomial (see Fig. 7).

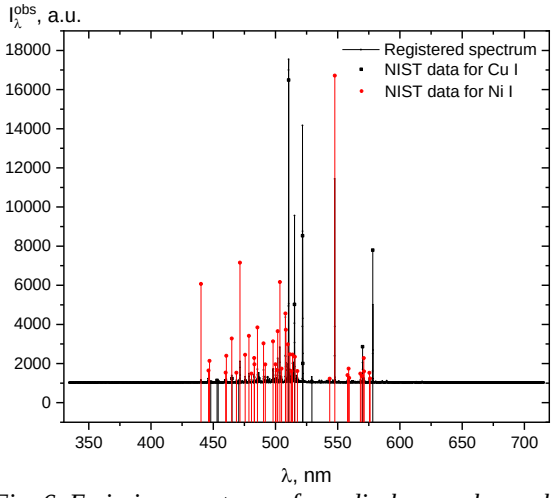

Fig. 6. Emission spectrum of arc discharge plasma between Cu and Ni electrodes with calibrated wavelength

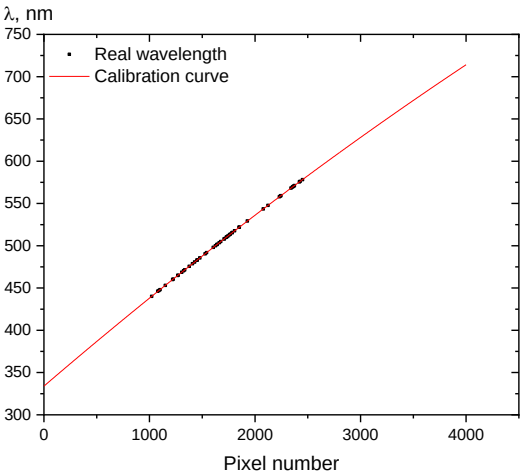

Fig. 7. Resulting calibration curve of the spectral registration device

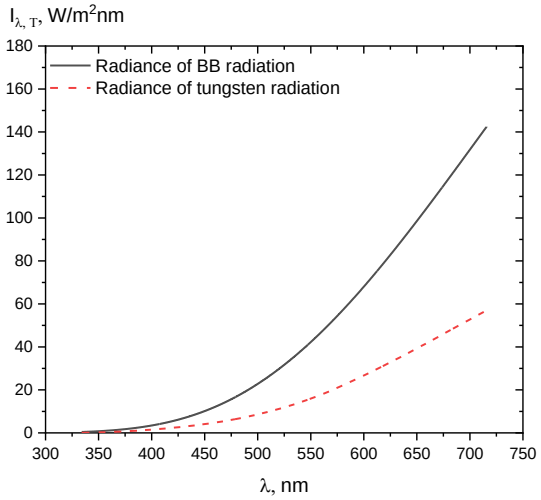

Fig. 8. Emission spectrum of blackbody and tungsten band of the reference lamp at a temperature of 2400 K

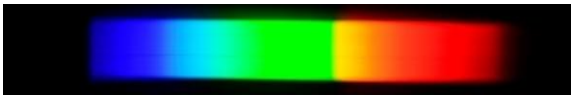

Fig. 9. RGB image of the tungsten band emission of the reference lamp at a temperature of 2400 K (exposure time 100 ms)

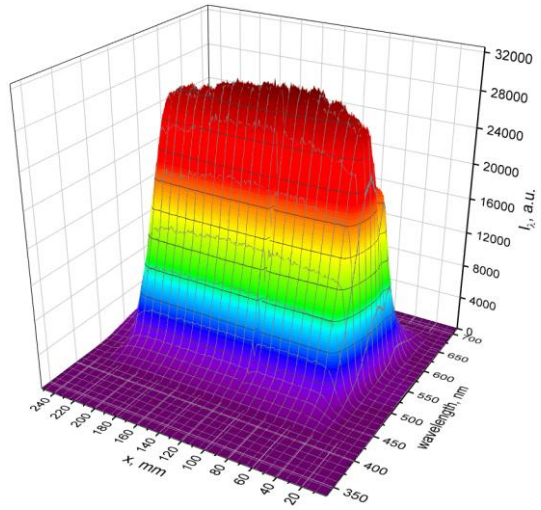

Fig. 10. Observed emission spectrum with spatial resolution (radial coordinate is presented in pixel numbers)

The obtained values of the wavelength for each pixel and the real radiation temperature were used to calculate the spectral distribution of the radiance of the blackbody emission $B_{\lambda,T}$ and tungsten I_λ from eq. (16) and (15), respectively (Fig. 8). The RGB image of the tungsten band emission at a temperature of 2400 K registered with an exposure of 100 ms is shown in Fig. 9. The observed emission spectrum in grayscale with spatial resolution is shown in Fig. 10. The observed spectrum in the centre of the tungsten band is shown in Fig. 11. In order to eliminate the noise caused by the fluctuations of the CMOS matrix due to heating, the emission spectrum was additionally smoothed as shown in Fig. 11.

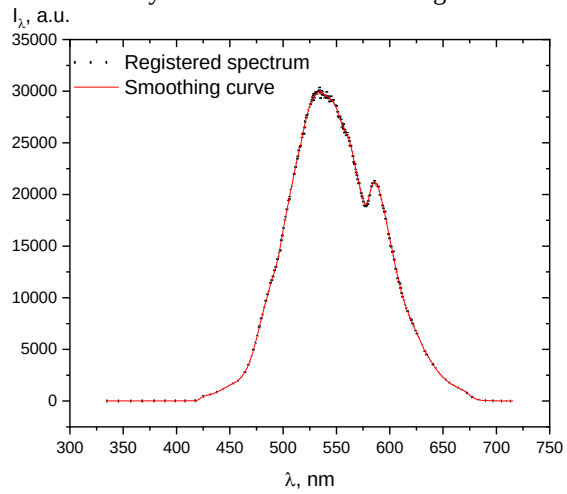

Fig. 11. Emission spectrum observed in the centre of the tungsten incandescent band

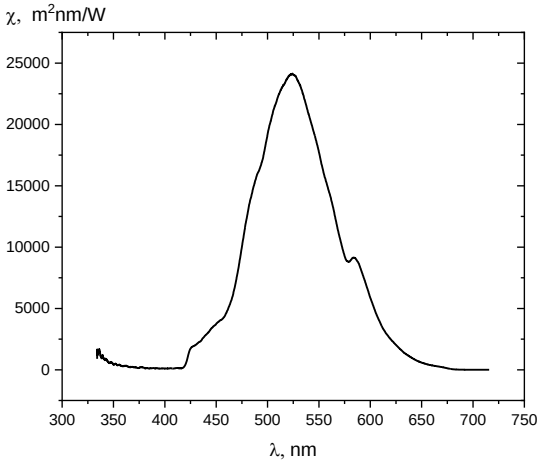

Fig. 12. Spectral sensitivity of the registration device

The spectral sensitivity of the proposed spectral device obtained according to eq. (14) is shown in Fig. 12.

It can be seen from the behavior of the spectral sensitivity, that the use of this spectral device is correct in the wavelength range of 430…650 nm. Since the spectral sensitivity goes to zero outside this range, its use in these regions of the spectrum is inexpedient.

3. DETERMINATION OF RADIAL DISTRIBUTIONS OF TEMPERATURE AND ATOMS' CONCENTRATION

An electric arc discharge burning in an argon flow between single-component copper electrodes was used to validate the method of determining the energy levels population and the concentration of atoms in the plasma of arc discharge from the absolute values of the emission intensity. The discharge was operated at an arc current of 3.5 A, a discharge gap of 8 mm, an argon flow rate of 7 *LPM*, an electrode diameter of 5 mm.

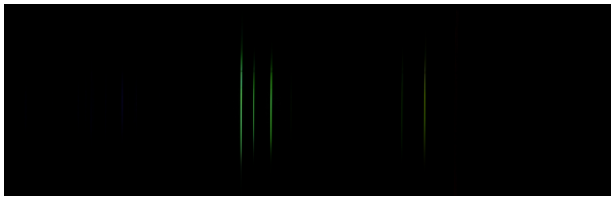

Fig. 13. RGB image of the plasma emission (exposure time 2 ms)

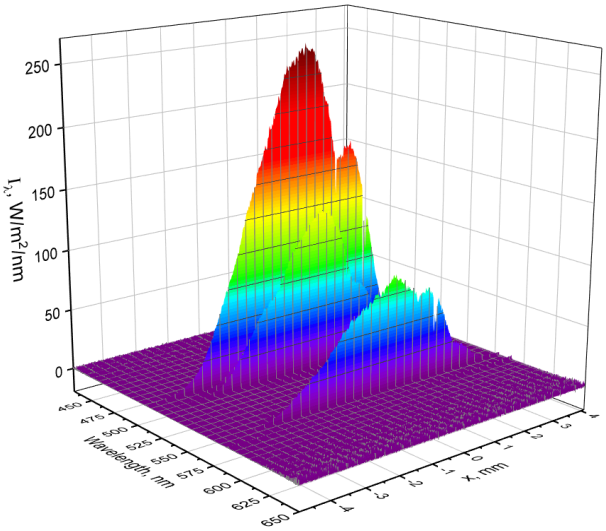

Fig. 14. Space-resolved emission spectrum of plasma (the spectral sensitivity of the device is taken into account)

The plasma emission of such a discharge was registered by the optical scheme shown in Fig. 1. The registered RGB image of the spectral emission of plasma with copper vapours admixtures is shown in Fig. 13. This image has been converted in the grayscale and the spectral sensitivity (see Fig. 12) has been taken into account. The space-resolved emission spectrum of the plasma obtained in such a way is shown in Fig. 14.

The boundaries of emission of spectral lines r_0 were determined according to the spatial coordinate for each registered copper spectral line, namely 510.5, 515.3, 521.8, and 578.2 nm. The obtained space intervals were separated into 9 equidistant segments. Thus, 10 spatial points, each of which contained the spectral distribution of radiance, was used for the further calculations. An approximation of contours of the spectral lines by the Gaussian function was used as it shown in Fig. 15 to determine the radiance of the corresponding lines. Spatial distributions of the radiance *I(x)* (Fig. 16) have been obtained by repeating the procedure for each spatial point and each Cu I spectral line. These distributions were approximated by the Gaussian function to obtain a smooth function, which was used to calculate the radial distributions of the emission intensity of spectral lines *ε(r)* according to eq. (10) by the Bockasten method [13] (Fig. 17).

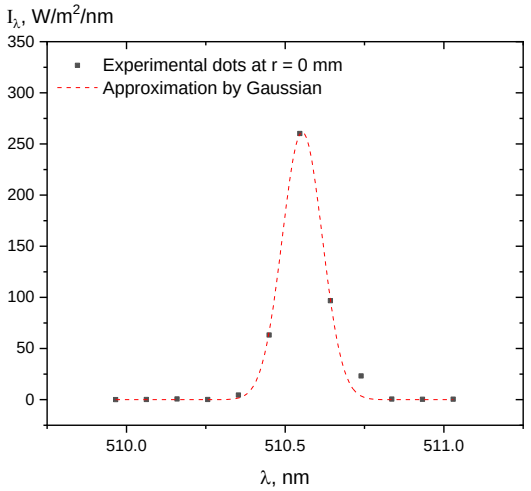

Fig. 15. Typical approximation of the Cu I 510.5 nm spectral line registered at the axis of the discharge channel

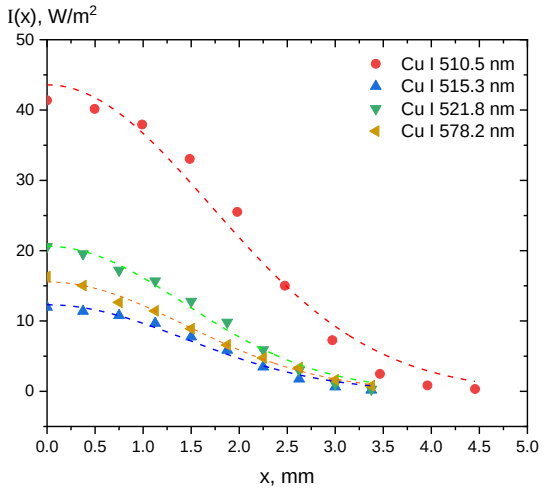

Fig. 16. Spatial distributions of radiance of copper spectral lines and their approximation by Gaussian function (dash lines)

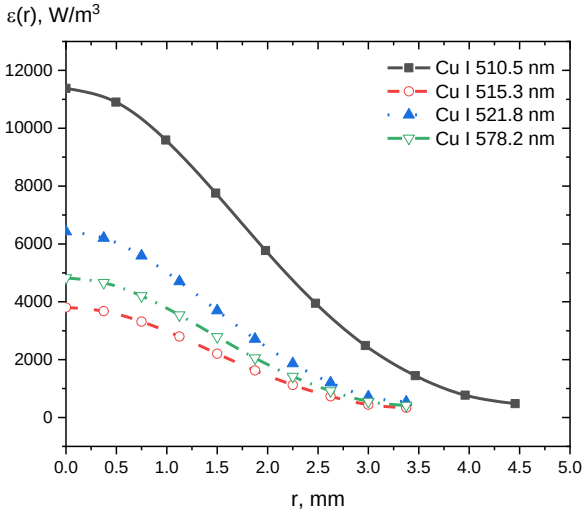

Fig. 17. Radial distributions of emission intensity of copper spectral lines

The obtained values of the emission intensity of each spectral line were used to determine the radial distributions of population of the upper energy levels *n(r)* corresponding to wavelength of the transition (Fig. 18) by eq. (2).

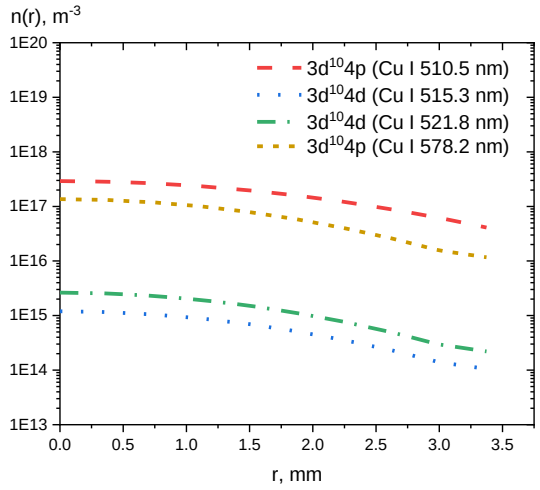

Fig. 18. Radial distributions of energy levels population of copper atoms

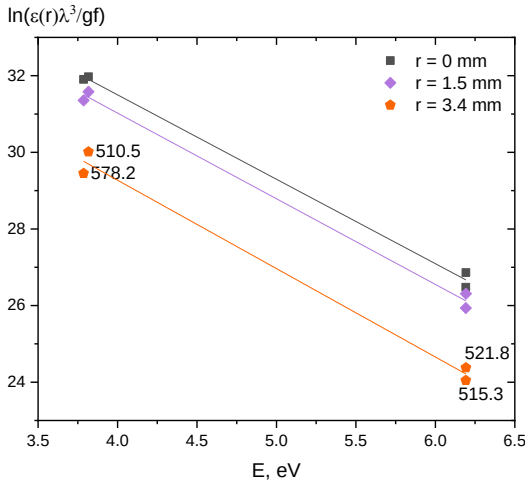

Fig. 19. Typical Boltzmann plots for different radial points on the basis of the absolute intensities of copper spectral lines

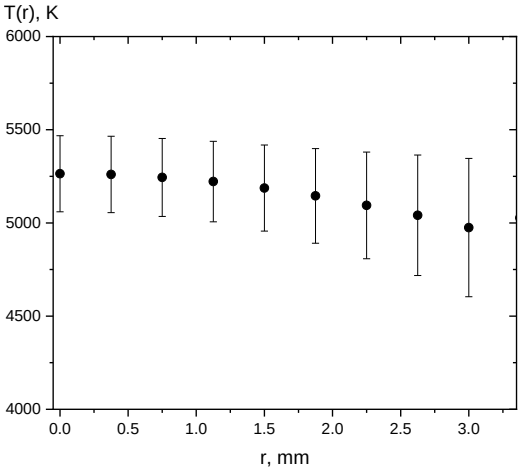

Fig. 20. Radial distribution of excitation temperature

The Boltzmann plot technique on the basis of the obtained absolute values of emission intensity of spectral lines has been applied according to eq. (6). The typical Boltzmann plot based on Cu I 510.5, 515.3, 521.8, and 578.2 nm spectral lines, constructed for different radial points of plasma emission are shown in Fig. 19. Thus, the radial distribution of the excitation temperature (Fig. 20) has been obtained by eq. (7). In turn, the concentration of copper atoms was determined by eq. (9)

using partition function obtained according to eq. (8) on the basis of known radial distribution of the temperature. Additionally, the radial distributions of concentrations were obtained on the basis of populations of copper energy levels (see Fig. 18) by eq. (3).

The radial distributions of the concentrations obtained in different ways are shown in Fig. 21. As one can see, the distributions obtained from the population of energy levels differ insignificantly from that one obtained by Boltzmann plot technique. The error bars for the last one were constructed assuming that the accuracy of the method is not less than 80%. One can see that such an assuming is correct for a distance from the axis of the arc up to 2 mm.

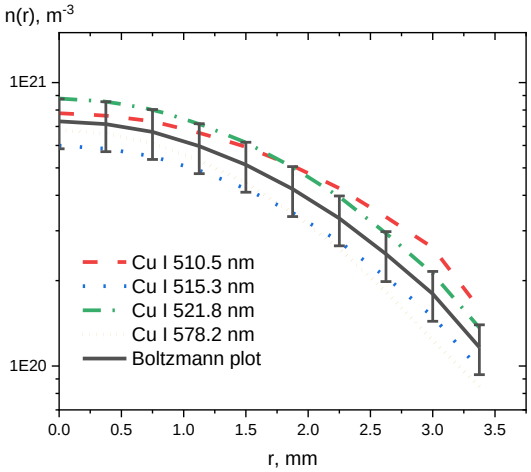

Fig. 21. Radial distributions of concentrations obtained by Boltzmann plot technique (shown with error bars) and from energy levels population of copper atoms

CONCLUSIONS

The alternative parameter to electron density for further calculation of the equilibrium plasma composition and the technique for its measuring have been proposed and described. Namely, the method for determining the atoms' concentration of metal vapours admixtures in the discharge gap from the absolute values of emission intensities has been considered. Additionally, a spectral device based on a spectrograph with a diffraction grating and a RGB CMOS matrix as a registration device has been applied to realize such a technique. The copper atoms' concentration has been determined in the plasma of electric arc discharge between single-component copper electrodes in the argon flow by Boltzmann plots technique based on the four spectral lines of Cu I and the determined excitation temperature. Moreover, the concentrations have been calculated from the population of copper's energy levels, determined directly from the absolute values of the emission intensity of these Cu I spectral lines. The results obtained by these two methods coincide within 20%, which gives grounds for recommending such a technique for plasma diagnostics of electric arc discharges.

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ДОСЛІДЖЕННЯ ПРОСТОРОВОГО РОЗПОДІЛУ ДОМІШОК ПАРІВ МЕТАЛІВ У ПЛАЗМІ ЕЛЕКТРОДУГОВОГО РОЗРЯДУ

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Робота присвячена діагностиці плазми електродугового розряду в потоці аргону методами оптичної емісійної спектроскопії. Описано та апробовано метод визначення заселеності енергетичних рівнів та концентрації атомів металу із абсолютних значень інтенсивності випромінювання спектральних ліній. Дослідження проводили з використанням спектрографа та RGB CMOS матриці як пристрою реєстрації випромінювання. Отримано абсолютні значення спектральної яскравості ліній Cu I, та з урахуванням осьової симетрії електродугового розряду визначено їх локальну інтенсивність випромінювання. Із залученням абсолютних значень інтенсивності випромінювання та радіального розподілу температури заселення, визначеної методом діаграм Больцмана, отримано радіальні розподіли концентрацій атомів міді. Розглянуто два методи розрахунку концентрації атомів. А саме, розрахунок із діаграми Больцмана на основі чотирьох спектральних ліній Cu I та визначеної температури заселення. З іншого боку, концентрацію отримано із заселення енергетичних рівнів міді, визначених безпосередньо із абсолютних значень інтенсивності випромінювання цих спектральних ліній Cu I. Результати, отримані цими двома методами, збігаються в межах 20%, що дає підстави рекомендувати дану методику для діагностики плазми електродугових розрядів.