doi:10.14311/ppt.2023.2.103
Plasma Physics and Technology **10**(2):103–106, 2023

INVESTIGATION OF PLASMA PARAMETERS USING OES AND SPECTRA SIMULATIONS

A. Murmantsev[a,*], A. Veklich[a], M. Baeva[b], V. Boretskij[a], V. Ninyovskij[a]

[a] *Faculty of Radiophysics, Electronics and Computer Systems, Taras Shevchenko National University of Kyiv, Volodymyrska str., 64/13, 01601, Kyiv, Ukraine*

[b] *Leibniz Institute for Plasma Science and Technology, Felix-Hausdorff-Str., 2, 17489, Greifswald, Germany*

[*] murmantsev.aleksandr@gmail.com

Abstract. The radiation from the arc plasma ignited between the flat ends of copper electrodes in atmospheric pressure air at a direct current of 3.5 A is analyzed to determine the plasma temperature and composition. Side-on spectra in the range (430 – 650) nm are recorded using a CMOS camera connected to a spectrograph. The spectral emission coefficient is evaluated from the spectral radiance, which provides the radiator number density. The excitation temperature is obtained by applying the Boltzmann plot technique to at least two spectral lines and a series of radial positions in the midplane of the arc. Subsequently, the plasma composition is determined. The equation of radiative transfer is solved along lines of sight considered in the experiment. The spectral intensity of Cu I lines is computed and compared with the experimental ones. The arc properties are obtained by assuming axial symmetry and mapping the evaluated values in the midplane.

Keywords: Arc plasma, optical emission spectroscopy, spectral profiles, radiative transport.

1. Introduction

Plasma diagnostics play a crucial role in understanding the behaviour and properties of plasmas in many applications [1]. Optical emission spectroscopy (OES) of plasma has become a powerful and widely used technique for the characterization and analysis of various types of plasma. In recent years, OES has found applications in diverse fields, including materials science, environmental monitoring, astrophysics, and plasma diagnostics in fusion devices. Its non-intrusive nature and ability to provide real-time measurements make it an attractive tool for in-situ monitoring and control of plasma processes.

One of the key areas where OES has shown remarkable progress is the investigation of arc plasma. Arc discharges are employed in plasma welding, cutting, and metal vapour generation for nanomaterial synthesis [2–4]. Detailed knowledge of arc plasma properties is therefore hugely important to the optimization of these processes, their efficiency and safety.

OES allows one to determine the main parameters of the plasma, such as temperature, electron density, concentration of plasma particles. One of the possible ways to determine these parameters is by comparing the registered emission spectra with the spectra computed by solving the radiative transfer equation (RTE). Since the spectra computation is associated with an iterative correction of the input parameters of the model in order to match the experimentally observed spectra, the computational procedure is challenging.

Similar studies have been carried out in previous published works. In [5], plasma parameters have been determined by assuming a homogeneous plasma and comparing observed and simulated spectra. The study has been limited to a pure copper plasma. The plasma pressure and temperature have been varied for the sake of accurate determination of the temperature of the optically thick plasma.

In this work, we focus on studying the emission of an inhomogeneous atmospheric pressure arc discharge plasma in air with copper vapour admixtures. The spectra were computed using the experimentally determined temperature and concentration of emitting atoms as an initial guess. The spectra computed along lines of sight relevant to the experiment were compared with the experimental ones. Consequently, the plasma parameters can be updated until the experimental spectrum is matched. Utilizing such an approach enhances our understanding of plasma properties and contributes to the development of more accurate plasma models.

2. Experimental and computational methods

The experimental study involves an arc discharge between the flat ends of copper electrodes with a diameter of 6 mm, placed at a distance of 8 mm from each other. The arc is ignited in air at atmospheric pressure with a direct current of 3.5 A. The optical emission spectroscopy setup consists of a diffraction grating (600 lines/mm) and a complementary metal-oxide-semiconductor (CMOS) matrix used as a registration device [6]. This configuration allows for the

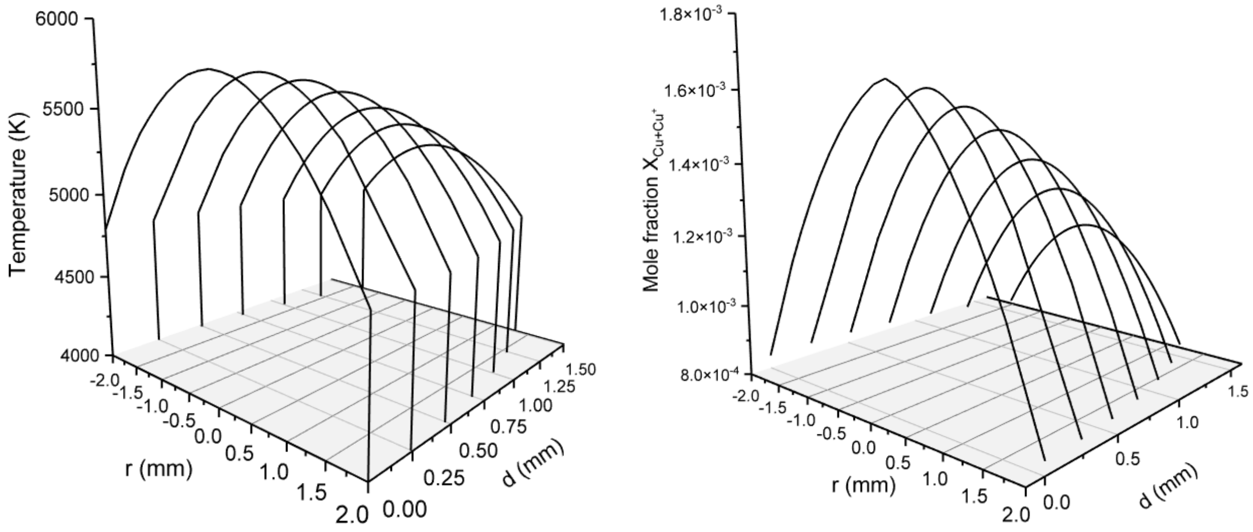

Figure 1. *Profiles of the plasma temperature (a) and mole fraction of Cu species (b) along lines of sight in a distance d from the arc centre.*

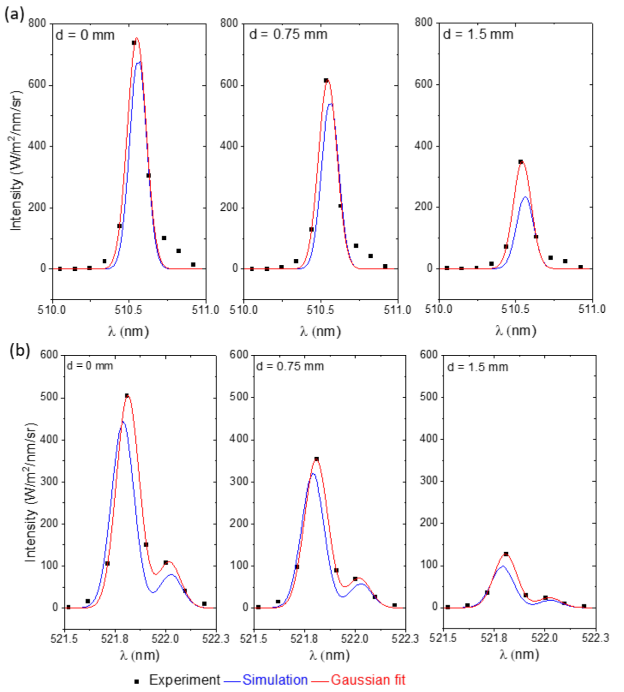

Figure 2. *Side-on profiles of Cu I spectral lines at (a) 510.5 nm and (b) 521.8 nm obtained in OES experiments (symbols and Gaussian fit) and computed for various distances d.*

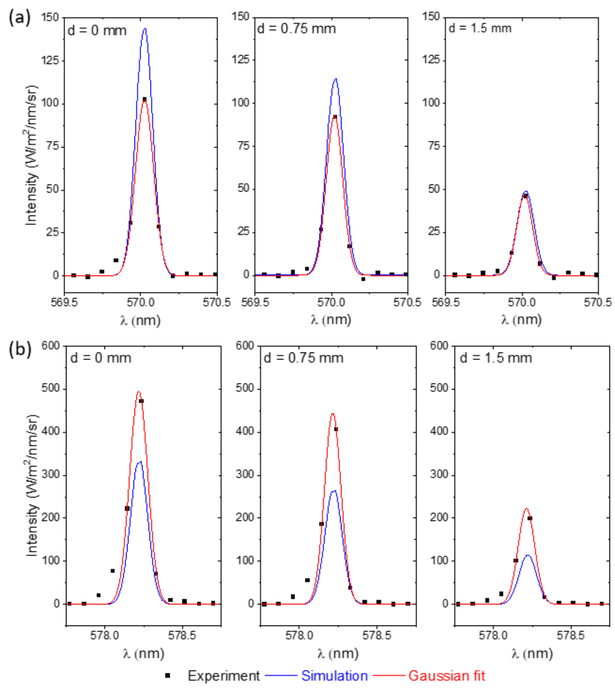

Figure 3. *Side-on profiles of Cu I spectral lines at (a) 570 nm and (b) 578.2 nm obtained in OES experiments (symbols and Gaussian fit) and computed for various distances d.*

collection of plasma emission data with both spectral and spatial resolution in the range of (430–650) nm. The spectral sensitivity of the CMOS matrix was calibrated using a tungsten ribbon lamp. The excitation temperature of copper atoms, which is equal to the plasma temperature under the assumption of local thermodynamic equilibrium, is determined using the Boltzmann plot technique based on the absolute intensities of Cu I spectral lines. The spectral emission coefficient is evaluated from the spectral radiance, providing the population of the emitting levels, and thus, the concentration of copper atoms is obtained by the method of absolute intensities of spectral lines [7]. The plasma temperature and composition determined in the midplane of the arc are then mapped assuming axial symmetry in order to reconstruct the corresponding profiles along lines of sight at a distance d from the arc axis (see Figure 1).

The experimentally obtained distributions of temperature and mole fraction of copper species are used as an initial guess for simulating the side-on spectra. This is achieved by solving the RTE [8, 9] and employing a line-by-line method. In this way, the change of the spectral radiative intensity I_λ along a line of sight into direction s in the case of no scattering is given as follows:

$$\frac{\mathrm{d}I_\lambda}{\mathrm{d}s} = \kappa_\lambda B_\lambda - \kappa_\lambda I_\lambda \tag{1}$$

where κ_λ is the spectral absorption coefficient, and B_λ is the Planck function. Atomic continuum due to Bremsstrahlung in electron-ion and electron-atom collisions, and atomic and ionic spectral lines are taken into account. Data for 1772 spectral lines, from which 57 are assigned to atomic copper Cu I, are considered [10].

It is worth noting that the plasma composition considered in the calculations involves not only species of copper but also species of nitrogen and oxygen. The composition has been determined based on the experimentally obtained radial distributions of temperatures and concentration of copper atoms under the assumption of local thermodynamic equilibrium.

The dominant broadening mechanism assumed is the Stark effect. However, due to the low current level, the broadening effect was not noticeable using the employed spectral device. Consequently, the spectral lines are fitted with a Gaussian shape, with a width of 0.13 nm, corresponding to the instrumental function. The spectroscopic data for the spectral lines of Cu I used in the simulation are taken from a previous work [11]. In general, the comparison of measured and computed spectra can be done iteratively, adjusting the profiles of temperature and mole fraction of copper species in cases where such profiles are not known from experiments.

3. Results and Discussions

The determination of the excitation temperature is initially done using the Boltzmann plot technique with the Cu I lines at 510.5 nm and 521.8 nm. Figure 2 shows the experimentally observed data points, along with the corresponding Gaussian fits and the computed spectra for these lines at several distances d from the arc centre. The experimental and computed spectra exhibit good agreement, although the experimental line intensities slightly exceed the computed ones, indicating a possible overestimation of the temperature. To further investigate the comparison, additional lines at 515.3 nm, 570.0 nm, and 578.2 nm are considered. Figure 3 presents the spectra of the lines at 570.0 nm (a) and 578.2 nm (b) for several distances d. The results show that the computed spectral line intensity appears close to or higher (Figure 3a) but also lower (Figure 3b) than the experimental one. Identifying the reasons for these discrepancies is challenging, and iterative computations with variations of the input parameters (plasma temperature, mole fraction of copper species) could be helpful.

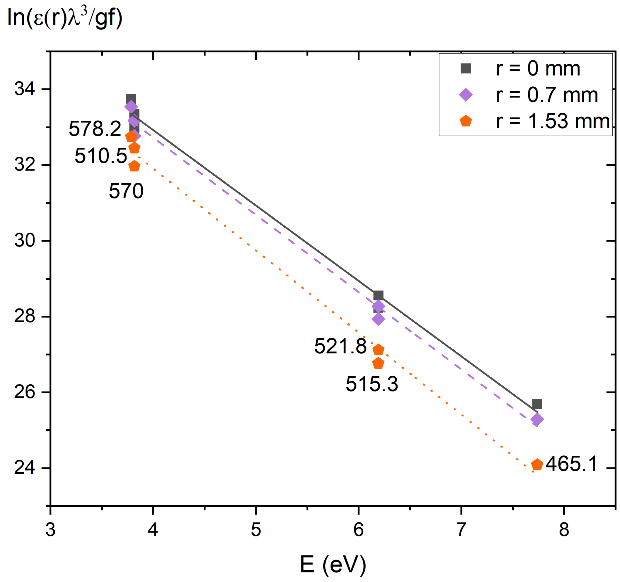

Figure 4. Boltzmann plots for the determination of the excitation temperature from Cu I spectral lines for various radial positions.

In order to understand the impact of each spectral line on the determination of the excitation temperature, five sets of spectral lines were defined for Boltzmann plots. Figure 4 displays the results for various radial positions and the involved spectral lines. It is important to note that the error in temperature evaluation, obtained from linear approximation, does not exceed 5%. Subsequently, individual spectral lines were removed from consideration one by one, and the temperature was recalculated using a reduced number of lines. The radial distributions of the temperatures obtained from different sets of spectral lines are shown in Figure 5. Despite the small measurement error of 5%, there is a discrepancy of approximately 10% in the radial temperature distributions obtained from sets 3 and 4. This difference suggests that inaccurate spectroscopic data, specifically the product of statistical weight and oscillator strength $g_i f_{ik}$, could also play a role [11]. Therefore, a powerful algorithm for iteratively determining accurate spectroscopic data for each spectral line can be developed by comparing experimentally obtained and simulated side-on spectra, along with the variation of $g_i f_{ik}$ as a simulation parameter, as provided in [11].

4. Conclusions

The study focuses on analyzing the arc plasma generated between copper electrodes in air at atmospheric pressure with a direct current of 3.5 A using optical emission spectroscopy and spectra simulations based on the equation of radiative transfer. The presence of copper species in the plasma is due to evaporation from the electrodes. By recording the emission

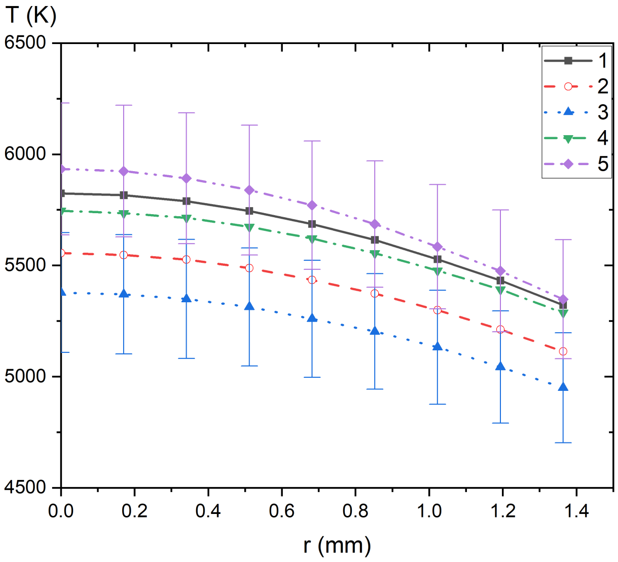

Figure 5. Radial distributions of the determined excitation temperature from various sets of Cu I spectral lines. 1- (465.1, 510.5, 515.3, 521.8, 570.0, 578.2) nm; 2- (510.5, 515.3, 521.8) nm; 3- (510.5, 515.3) nm; 4- (510.5, 521.8) nm; 5- (465.1, 510.5) nm.

from copper atoms along perpendicular lines of sight to the arc axis, the plasma temperature of copper atoms is determined, assuming local thermodynamic equilibrium.

Using the plasma temperature and concentration of copper species, the spatial distribution of arc properties can be reconstructed. The agreement between experimental and computed spectral line intensities is generally good, with discrepancies of up to 30% observed for specific spectral lines like Cu I 570.0 nm and 578.2 nm. These discrepancies may arise from uncertainties in spectroscopic data and plasma parameters, potentially caused by deviations from axial symmetry. However, this study does not account for deviations from local thermodynamic equilibrium.

The comparison between experimentally obtained and simulated side-on spectra, while varying plasma parameters and spectroscopic data, serves as a powerful tool for reconstructing plasma properties and critically evaluating spectroscopic data. It highlights the importance of considering various factors and fine-tuning the simulations to improve the accuracy of plasma property determination.

Acknowledgements

The financial support by the German Research Foundation DFG (Project number 455483754) is greatly acknowledged.

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.

References

[1] M. Baeva, V. F. Boretskij, D. Gonzalez, et al. Unified modelling of low-current short-length arcs between copper electrodes. *Journal of Physics D: Applied Physics*, 54:025203 (11pg), 2021. doi:10.1088/1361-6463/abba5d.

[2] A. Murphy. The importance of the arc, unresolved questions and future directions. *Plasma Chemistry and Plasma Processing*, 35:471–489, 2015. doi:10.1007/s11090-015-9620-2.

[3] B. Heider, M. Oechsner, U. Reisgen, et al. Corrosion resistance and microstructure of welded duplex stainless steel surface layers on gray cast iron. *Journal of Thermal Spray Technology*, 29:825–842, 2020. doi:10.1007/s11666-020-01003-y.

[4] N. Arora and N. Sharma. Arc discharge synthesis of carbon nanotubes: Comprehensive review. *Diamond and Related Materials*, 50:135–150, 2014. doi:10.1016/j.diamond.2014.10.001.

[5] S. Franke, R. Methling, D. Uhrlandt, et al. Temperature determination in copper-dominated free-burning arcs. *Journal of Physics D: Applied Physics*, 47:015202 (12pp), 2014. doi:10.1088/0022-3727/47/1/015202.

[6] A. Murmantsev, A. Veklich, V. Boretskij, et al. Investigation of thermal plasma of arc discharge between novel composite Cu-W materials. *Problems of Atomic Science and Technology. Series: Plasma Physics (29)*, 143(1):74–78, 2023. doi:10.46813/2023-143-074.

[7] A. Murmantsev, A. Veklich, V. Boretskij, et al. Diagnostics of plasma of electric arc discharge between asymmetric single-component Cu and Ni electrodes. *Problems of Atomic Science and Technology. Series: Plasma Physics (29)*, 143(1):117–121, 2023. doi:10.46813/2023-143-117.

[8] D. Uhrlandt, G. Gött, R. Kosakov, et al. Study of radiation of high pressure arcs. *XXth Symposium on Physics of Switsching Arc, Invited lectures*, pages 49–57, 2013.

[9] M. F. Modest. *Radiative heat transfer*. Elsevier Inc. Amsterdam, 2013.

[10] A. Kramida, Yu. Ralchenko, J. Reader, and and NIST ASD Team. NIST Atomic Spectra Database (ver. 5.10), [Online]. Available: https://physics.nist.gov/asd [2023, August 2]. National Institute of Standards and Technology, Gaithersburg, MD., 2022.

[11] I. Babich, V. Boretskij, A. Veklich, and R. Semenyshyn. Spectroscopic data and stark broadening of Cu I and Ag I spectral lines: Selection and analysis. *Advances in Space Research*, 54:1254–1263, 2014. doi:10.1016/j.asr.2013.10.034.