Spectral investigation of atmospheric pressure helium arc plasma parameters

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Due to increasing demand in arc discharges and appearance of additional applications, methods for accurate determination of their properties are also being needed. This work presents a complex of optical measurements which allows addressing this challenge. We present methods, measurement results and their interpretations. We also consider the accompanying problems and suggest methods for their solutions.

In our work, helium was selected as a working gas for being frequently used in medical and other applications and for being insufficiently studied in high-current arcs at high ionization levels which are hard to obtain. The arc current strength in this work will be from 250 A to 400 A, which provides plasma temperatures of 2..2.5 eV and ionization levels up to 50%, as will be shown further.

Experiments were carried out on a DC arc plasmatron with an expanding anode channel (d = 0.5 mm) and vortex arc stabilization. Helium flow was about 0.2 g/s. The studied arc region was located in 1..3 mm from the tip of the tungsten cathode. It was observed through two quartz glass windows located symmetrically in the plasmatron nozzle wall. The radiation spectra were observed with a three-channel AvaSpec spectrometer and high-resolution DFS-452 spectrograph with a high-speed Andor camera fitted to its output. The AvaSpec spectrometer allows to register the spectra in a wide wavelength range (200..1100 nm) with the varying resolution of 0.23..0.29 nm. The DFS-452 was used with narrow input slit setting (10..25 µm), camera matrix pixel size was 25 µm. The apparatus functions of the registration system were determined beforehand by using a hollow cathode lamp emitting spectral lines no wider than 0.02 Å. For the diffraction lattice with 1200 lines per millimeter the apparatus function was found to be $\delta_{app} = 0{,}2 \pm 0{,}03$ Å, for one with 600 lines per millimeter it was found to be $\delta_{app} = 0{,}35 \pm 0{,}05$ Å. In this way, the Andor camera registered the spectrum in a narrow wavelength range of about 40 nm with high resolution. Its additional advantage was that the spectrum was registered on a matrix, this allowing to observe the radiation intensity distribution over the arc radius. The spectra obtained with the described devices are shown in fig. 1 and 2.

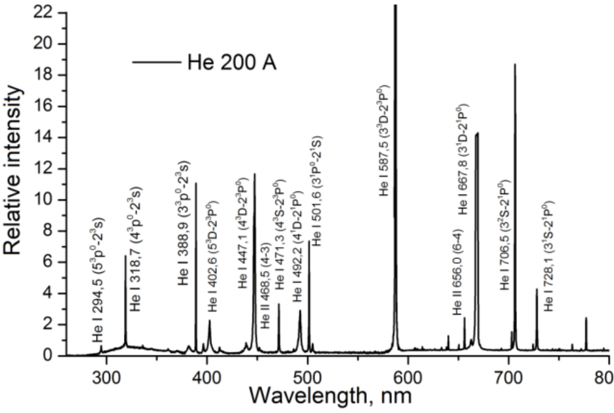

Fig. 1. A typical spectrum obtained with AvaSpec spectrometer.

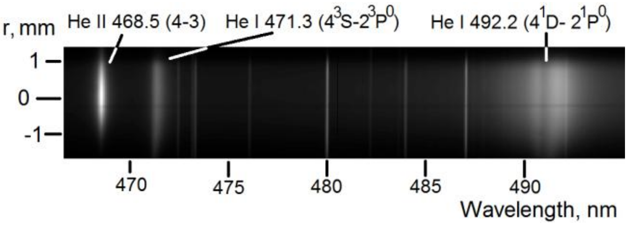

Fig. 2. A typical spectrum obtained with the Andor camera and DFS-452 spectrograph.

The obtained spectra were processed with the developed automated analysis software which was able to perform the following operations without the input from the user:

- Determine spectral line peak locations on the experimental spectrum;
- Find matches between lines from the database [1] and found lines of the experimental spectrum;
- The chordal line contour is converted into radial by means of Abel transform;
- Approximate every experimental line contour with the Voight function [2], thus obtaining its Gauss and Lorenz components [3] and corresponding parameters from their widths;
- Line intensity is then found by integrating the found approximation function, continuum intensity is taken as approximation function value at large distance from line center.

The notable features of the observed spectra are as follows. The radiation intensity of continuum and HeI lines increases comparably little as the arc current increases from 250 to 400 A. The line that shows largest intensity increase is HeII 468.6 nm. The width of HeI lines increases monotonously as the arc current increases. The electron concentration n_e was found from the half-width of the HeI lines with the dominating widening quad Stark-effect and well-known Stark widening constants (namely lines at 318.7, 388.8, 402.6, 471.3, 492.2, 501.5, 667.8, 706.5, 728.1 nm) [4, 5]. For atomic lines the quad Stark effect is given by

$$\delta\lambda_{St}=\alpha_{st}\cdot n_e \quad (1)$$

For He ions the linear Stark effect takes place:

$$\delta\lambda_{St}=\alpha_{st}\cdot n_e^{2/3} \quad (2)$$

The distribution of electron concentrations over the arc radius obtained with this method is shown in fig. 3.

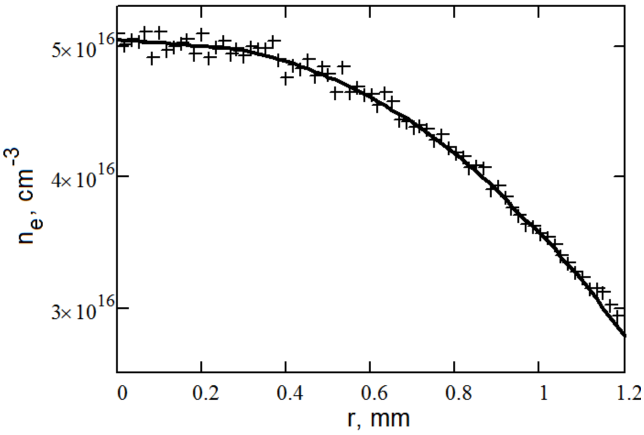

Fig. 3. Radial distribution of electron concentration n_e. + – calculated points,the line shows the approximation function.

In most experimental works the high-ionization state of He plasma (with temperatures of 20000..50000°K) was obtained in impulse discharges with pulse times of $10^{-4}..10^{-6}$ μs at which the local thermodynamic equilibrium state could not be achieved. The reasons of deviations from the equilibrium state (at which Boltzmann law and Saha equations are valid) for He plasma are very high excitation and ionization levels of atoms and ions as well as high values of thermal conductivity coefficient λ and diffusion coefficient D_a. The analysis of the reasons He plasma deviates from the local thermodynamic equilibrium and population features of HeI states is done in works [10, 11]. In [12] it is noted that high states (n>5) tend to equilibrium with continuum while lower states are overpopulated. This statement is experimentally proved in [13]. For the case of helium the deviation from the equilibrium state is substantial even at conditions when other plasmas (argon, for instance) do not strongly display such properties [10, 11, 14]. The authors of these works suggest custom methods for analyzing such phenomena based on simple analytic estimates. However, that approach is too approximate for quantitative analysis of experimental spectral data. In [12] a so-called modified diffusion approach with solving the system of balance equations is suggested as a method for describing the population of excited states. In this model the set of discrete energy levels is replaced with a continuous distribution what can be justified for high-energy states. As a result, this approach produces a χ-function which denotes the difference between the real distribution and the one given by Boltzmann equations for equilibrium state.

$$\chi(x) := \frac{4}{3\cdot\sqrt{\pi}}\cdot\int_0^x e^{-t}\cdot t^{\frac{3}{2}}\,dt \quad (3)$$

This can be used to determine electron temperature from the experimentally obtained populations of pairs of excited states using the following formula:

$$T_e = \frac{E_2 - E_1}{\ln\left[\chi\left(\frac{E_2}{T_e}\right)/\chi\left(\frac{E_1}{T_e}\right)\right] + n_1 g_1 - n_2 g_2} \quad (4)$$

The electron temperature found with this method for arc current of 250 A was T_e =2.2 eV.

Conclusion

In this work we have been able to achieve stationary states of highly ionized helium plasma at atmospheric pressure with electron concentration $n_e \le 10^{17}$ cm^{-3} at T_e=2..2.5 eV, have studied its radiation properties and discussed possible methods of determining electron temperature from the spectral data. The radial electron distributions for such plasma at a non-equilibrium state was obtained. The value of plasma temperature was obtained with the modified diffusion approach and it agrees with the estimate made from the Doppler component of the spectral lines with low values of Stark widening coefficient. This analysis was carried out on a HeI triple line at 1083 nm (2^3P–2^3S transition).

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