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Spectroscopic Studies of a Helium Plasma Generated Near Ceramic Surface at Pressures Below 1000 hPa

J. Musielok, H. W. Janus, and W. Jeleński

Institute of Physics, Pedagogical University Opole, ul. Oleska 48, PL-45-052 Opole, Poland

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Abstract. Spatially resolved line intensity measurements from a plasma generated near ceramic surfaces have been performed. Disk-shaped helium plasmas of diameter 20 mm and thickness 0.9 mm have been studied in a pressure range of 2×10^3–10^5 Pa. On the basis of line intensity measurements and applying an appropriate collisional–radiative model for a helium plasma, the distributions of electron density and electron temperature have been evaluated.

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The plasma generated near a ceramic surface has been the subject of several papers in recent years [1–8]. To date almost exclusively plasmas at atmospheric pressure have been studied. In one of our previous papers, the distributions of excited atoms and ions in a plasma consisting of helium, argon and hydrogen were studied [5]. The gradients obtained are different for different emitters (various elements and ionization stages) and for a fixed emitter they differ from line to line. In particular it has been found that for a given spectral line the gradient does not depend on the total distance between the two ceramic plates [5]. In a recent paper [8], the temperature and electron density in a helium plasma at atmospheric pressure were measured. The determination of these plasma parameters was based on line intensity measurements applying an appropriate collisional–radiative model for the helium plasma. The gradients obtained for these plasma parameters were interpreted in terms of the specific plasma generation mechanism.

The gas pressure in the discharge volume is a crucial parameter in any plasma source. The aim of this work is to study the spatial distribution of excited helium atoms in a plasma generated near ceramic surfaces at pressures lower than atmospheric pressure. On the basis of these measurements the most important plasma parameters: electron density and electron temperature are evaluated.

1. Experiment

The plasma source consisting in principle of two plane parallel ceramic plates is schematically shown in Fig. 1. The outer surfaces of the ceramic plates are provided with electrodes. The electrode areas and the space between the inner ceramic surfaces limit the dimensions of the plasma. The electrodes are supplied with an external ac voltage of the order of some hundred volts. The ceramic plates are located in a vacuum-tight chamber, which allows one to generate the plasma at different adjustable gas pressures. The plasma generated in this way also shows a very good stability and reproducibility.

In this work the distance between the inner surfaces of the ceramic plates was 0.9 mm. The diameter of the circular electrodes was 20 mm. Helium was used as a working gas at pressures in the range 2.5×10^3–10^5 Pa. Below the lower limit (2.5×10^3 Pa) the discharge character changes drastically, which manifests itself by sudden unreproducible discharges outside the normal discharge volume. The plasma was generated at several pressure values, applying an external voltage at a frequency of 10 kHz. The voltage value was adjusted for each experiment (each pressure) such that the charge density measured at one of the electrodes was the same for all experiments. A calibrated thermocouple was attached to one of the electrodes in

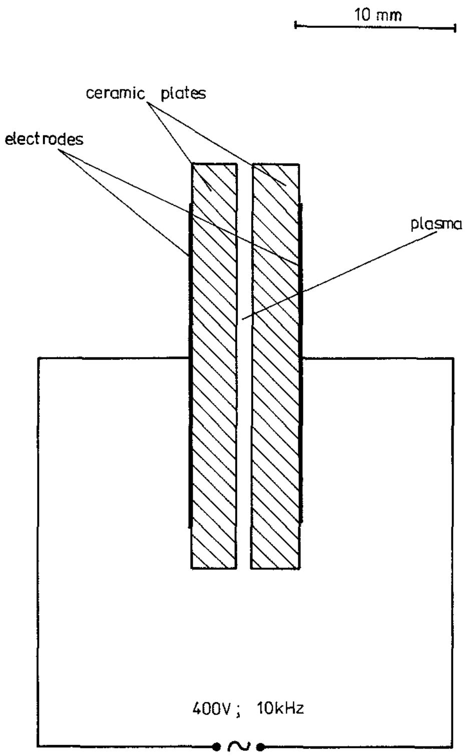

Fig. 1. Schematic of the setup for plasma generation

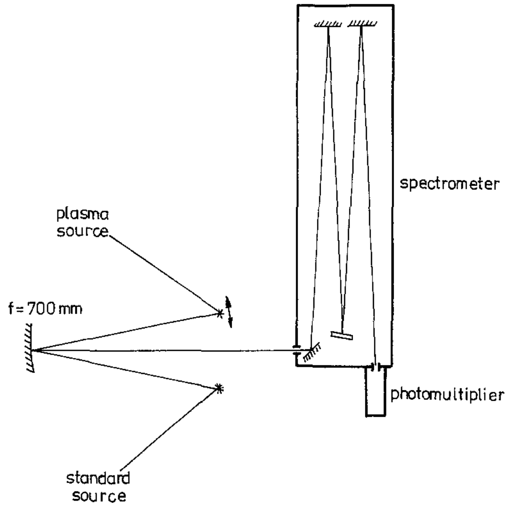

Fig. 2. Schematic of the optical alignment applied for measurements of spectral line intensity distributions in the plasma. The arrows show the drive direction of the source

order to control the temperature of the ceramic plates. The measurements were performed at stationary temperatures. The temperature values measured in this manner change from 380 K to 410 K in the whole pressure range.

We assume that the plasma is homogeneous in the direction parallel to the ceramic surfaces. This assumption is based on the following arguments: (i) from the plasma generation mechanism, described in [1], one may infer that the plasma parameters should depend on the distance from the ceramic surface; (ii) the above conclusion is supported by our previous measurements [5], where it was shown that the gradients of the line intensities in the direction perpendicular to the surfaces do not depend on the total plate separation; and (iii) the length of the plasma column (parallel to the surfaces) is large compared with the boundary plasma layers.

Figure 2 shows schematically the detection system employed. The plasma source is precisely located on the optical axis of the grating spectrometer PGS-2, keeping the ceramic surfaces parallel to the optical axis. Applying a suitable drive, the plasma source could be moved perpendicular to the optical axis. The light emitted by the plasma is focused on the entrance slit of the spectrometer, through a concave mirror ($f = 700$ mm) with a magnification of 1.4. A narrow rectangular diaphragm, placed in front of the mirror and the spectrometer entrance slit, guarantees measurements with high spatial resolution – better than 0.05 mm (in the direction perpendicular to the ceramic surfaces).

The measured He-spectrum shows, besides He I lines, also N_2 and N_2^+ molecular bands originating from impurities contained in the technical purity working gas. The continuum intensity near the visible and UV He I spectral lines was negligibly small. Therefore the line intensity distribution (total intensity) of the He I line in the discharge volume was measured by setting the spectrometer on the chosen wavelength (the exit slit encloses the whole spectral line) and moving the plasma source by the drive coupled with a chart recorder drive. In this way the distribution of the He I spectral line in the plasma volume was measured for various pressures. However, it should be noted that very close to the ceramic surfaces ($x < 0.05$ mm) the photomultiplier current (which is proportional to the line intensity) underrates the true value of the line intensity. This is caused by a decrease in the effective length of the plasma layer from which the light is collected and directed to the spectrometer slit. Therefore in this paper only results for distances from the ceramic surface larger than 0.05 mm are presented. Using a low-current carbon standard arc after Euler [9], the measured relative line intensities could be converted to an absolute scale.

2. Results of Line Intensity Measurements

The He I spectral line at 501.6 nm (singlet transition 2^1S–3^1P^0) was chosen for measurements of the distribution of excited helium atoms in the plasma volume. The measured line intensity distributions were symmetrical for all applied gas pressures. Therefore only results for the half of the discharge volume are given below. Figure 3 shows the measured emission coefficient of the He I 501.6 nm line as a function of the distance from the ceramic surface at 7 different values of the pressure. As can be seen, the population of the level 3^1P^0, which is responsible for the emission of the line, changes dramatically with pressure, particularly in the center of the discharge volume ($x = 0.45$ mm). The dependence of the emission coefficient on pressure for 4 fixed distances from the ceramic surface is shown in Fig. 4. Both Figs. 3 and 4 illustrate the complexity of the excitation mechanism in the studied plasma source.

The number of excited He atoms in the 3^1P^0 state could be calculated by using the corresponding probability for this spectral transition [10]. In the studied pressure range (26.7–778 hPa) with decreasing pressure (decreasing total number of He atoms) the number of excited atoms increases in the average by a factor of 20 and in the center of the discharge volume even by a factor of 100.

The number of atoms in the ground state 1^1S is approximately equal to the total number of the plasma particles. For each experiment this number was calculated on the basis of (i) the gas pressure and (ii) the temperature measured with the thermocouple, assuming that this temperature is nearly the same as the gas temperature. This last assumption was recently confirmed by Łopatka [11] by interferometric line broadening measurements of He I lines. The dominant agent for He I line broadening in the studied plasma source is the Doppler broadening. In this way the gas temperature was evaluated, showing a good agreement with the values obtained applying the thermocouple. In Fig. 5 we show the ratio of the number of excited He atoms in the 3^1P^0 state and the number of He atoms in the 1^1S ground state as a function of the distance from the ceramic surface. This quantity gives information about the excitation efficiency into the 3^1P^0 He state at various distances from the ceramic surface as well as at various gas pressures. In the studied pressure range this efficiency changes by a factor of 100 near the ceramic surface, and in the discharge center even by a factor of 3000.

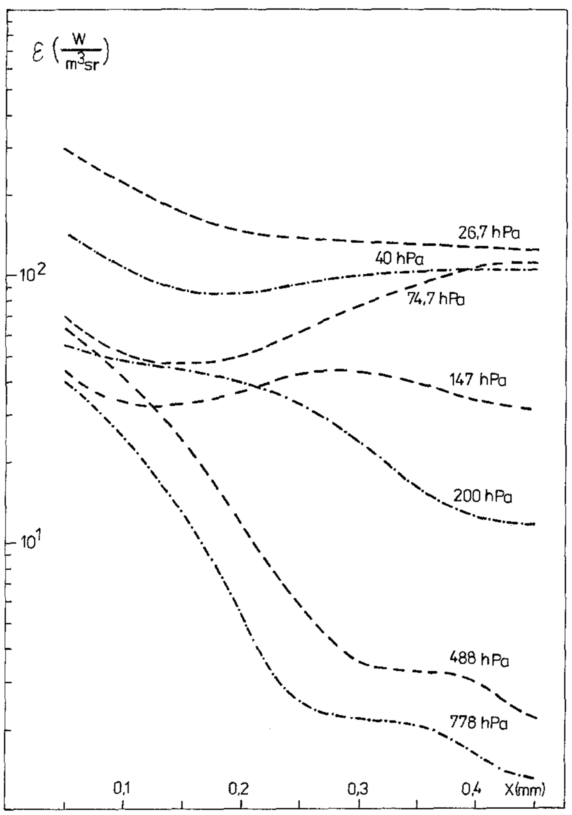

Fig. 3. The emission coefficient distributions of the He I 501.6 nm spectral line in the He plasma generated under various pressure values. The distance x is counted from the ceramic surface

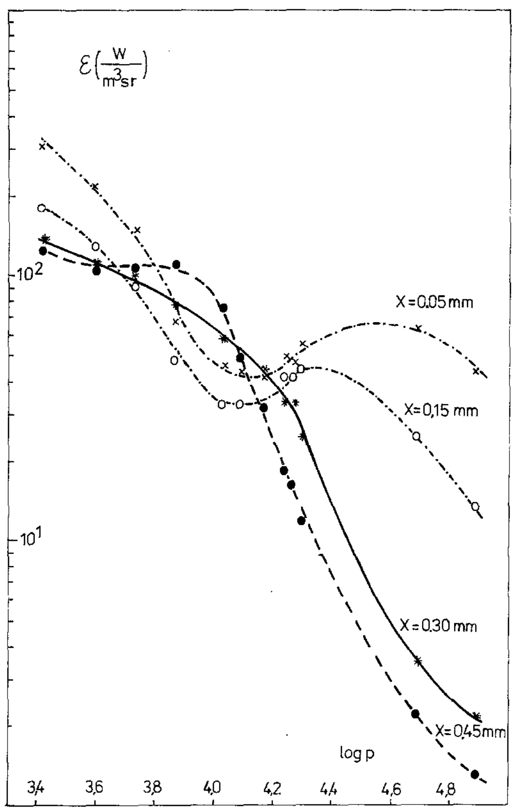

Fig. 4. The dependences of the emission coefficients of the He I 501.6 nm spectral line on the gas pressure for fixed distances from the ceramic surface

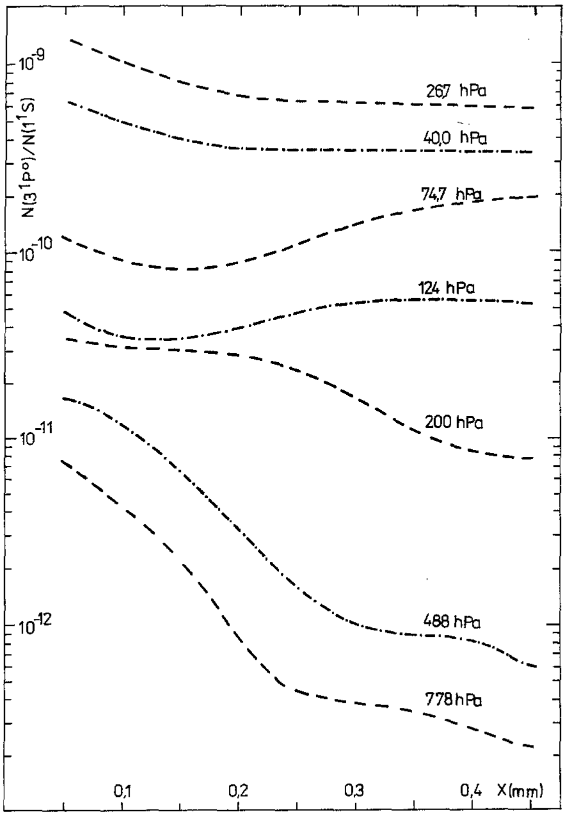

Fig. 5. The ratio $N(3^1P^0)/(N(1^1S)$ as a function of the distance from the ceramic surface at different pressures. The ratio illustrates the efficiency of the excitation into the 3^1P^0 level of He I for various pressures and various distances from the ceramic plate

3. Electron Temperature and Electron Density Determination

The studied plasma cannot, of course, be described with the LTE model. The expected electron temperature is at least one order of magnitude larger than the gas temperature. The electron temperature (T_e) and electron density (N_e) were determined by assuming that:

(i) the population of excited He atoms is described by the collisional–radiative model for a helium plasma proposed by Srivastava and Ghosh [12],

(ii) the ionization balance can be calculated on the basis of the updated evaluation of ionization equilibria performed recently by Arnaud and Rothenflug [13],

(iii) the electron density and the ion density are the same.

According to the collisional–radiative model, the population of a selected excited level is given by the corresponding value of the Saha-decrement defined as:

$$\varrho(p) = n(p)/n_E(p), \tag{1}$$

where $n(p)$ is the true level population and $n_E(p)$ is the equilibrium population given by the formula

$$n_E(p) = N_i \cdot N_e \cdot [g(p)/2\omega_i] \times (h^2/2\pi mkT_e)^{3/2} \exp(\chi_p/kT_e). \tag{2}$$

In the above equations p represents the quantum numbers n, L, and J of the selected level, $N_e = N_i$ is the electron (ion) density, g and ω_i are the statistical weights of the selected level and the ion partition function, χ_p is the ionization energy of the excited level under consideration. Other symbols have their usual meaning.

In the paper of Srivastava and Ghosh, the Saha-decrement is presented graphically as a function of electron density for fixed temperature values. On the basis of these results it is possible to evaluate the corresponding Saha-decrement for given N_e and T_e values. On the other hand, the data for ionization equilibria evaluated by Arnaud and Rothenflug allow one to calculate, for a given temperature, the ratio N_i/N_0, where N_0 is the density of helium atoms. These data, together with (i) the measured population density of the excited 3^1P^0 level, (ii) the value of the gas pressure and (iii) the measured gas temperature, complete the system of equations for determination of the electron density and electron temperature of the plasma. Because both desired parameters N_e and T_e are unknown, the system of equations was solved by the method of successive approximations. These calculations were performed for all experiments (all gas pressures) and for various distances from the ceramic surface. The results for 7 pressure values are shown in Figs. 6 and 7 for electron density and electron temperature, respectively. The electron density ranges from $10^{18}\,\mathrm{m}^{-3}$ to $3\times10^{20}\,\mathrm{m}^{-3}$. The gradients are rather strong in the case of larger pressure values. At pressures below 50 hPa about two-thirds of the plasma volume (around the center) is nearly homogeneous. The electron densities obtained for the plasma center at lower gas pressures agree well with the value obtained recently by Łopatka [11] based on broadening measurements of the H_β line in a helium plasma (with small admixture of hydrogen) generated in the same experimental conditions (the same distance between the plates) and at nearly the same pressure (2.4×10^3 Pa). The electron density distribution for the pressure of 778 hPa agrees well with the distribution obtained in [8] for a plasma at atmospheric pressure. The electron temperature distributions show rather weak gradients. As could be expected, with decreasing pressure the electron temperature increases. The extrapolation of our results to a pressure of 1000 hPa leads also to a good agreement with results obtained in [8].

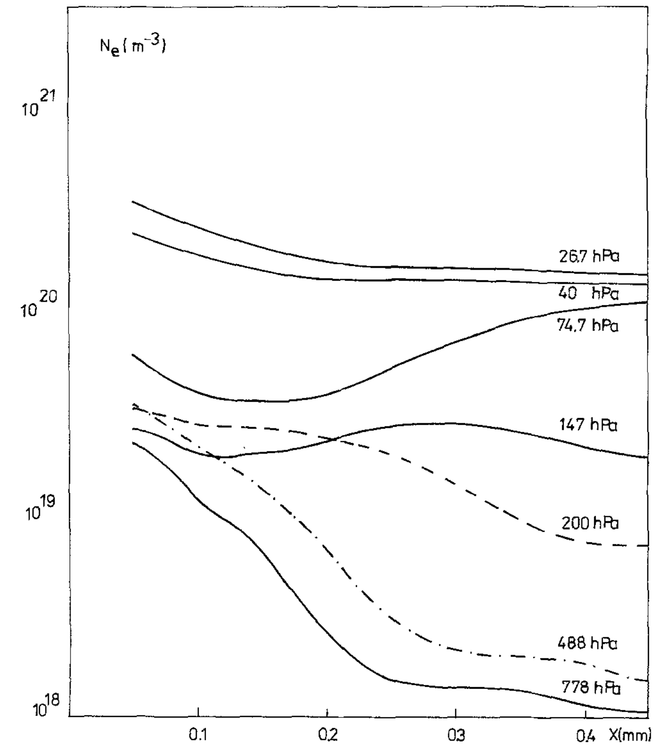

Fig. 6. The electron density of the plasma as a function of the distance from the ceramic surface at different pressures

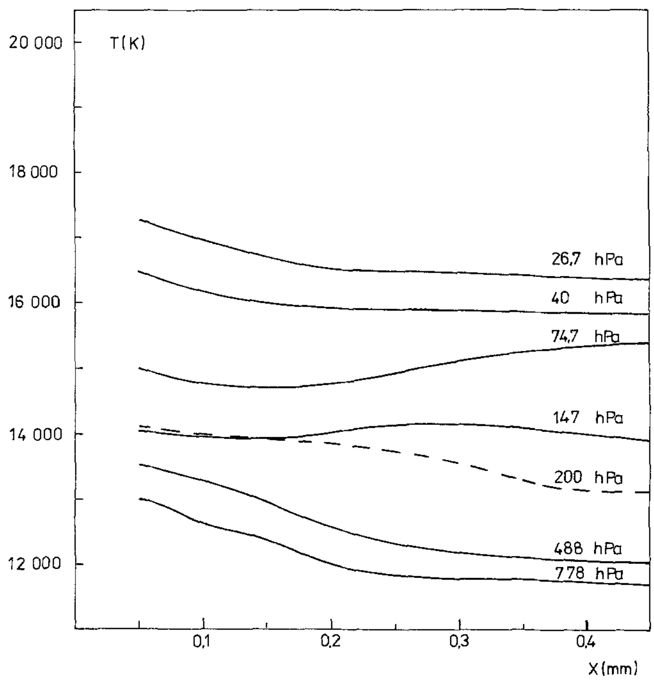

Fig. 7. The electron temperature distributions in the plasma for various pressures

4. Discussion

For N_e and T_e determination the "optically thick" data of the collisional–radiative model were applied. The densities of He atoms in the ground state 1^1S ($5\times10^{23}-1.5\times10^{26}\,\mathrm{m}^{-3}$) are large enough for self-absorption of the most important VUV resonance lines at 58.4 nm (transition $1^1S-2^1P^0$) and at 53.7 nm (transition $1^1S-3^1P^0$).

The visible line at 501.6 nm itself, chosen for the measurements, is not affected by self-absorption. This was checked by:

(i) inserting a mirror perpendicular to the optical axis on the back side of the plasma source – the increase of the measured signal corresponds to the reflectivity of the applied mirror,

(ii) moving the plasma source along the spectrometer slit, changing in this manner the length of the plasma column (round electrodes), from which the light is directed to the spectrometer – the measured line intensity was exactly proportional to the length of the plasma column.

For the measurements the line at 501.6 nm was chosen because the sensitivity of our detection system for this wavelength is better than for other He lines (even stronger in absolute intensity units). Choosing this line, we could measure the intensity distributions with sufficient spatial resolution in the whole pressure range. In order to make our results, obtained on the basis of the intensity measurements of the 501.6 nm line, more credible, we measured the intensities of 6 other He I lines emitted from the central layer of the plasma at a pressure of 107 hPa. The measurements were performed at lower spatial resolution in order to get sufficiently large signal output from the photomultiplier. Since the gradients of the plasma parameters in the center of the discharge volume are rather weak, the reduction of the resolution hardly influences the quality of the data. The plasma parameters (N_e and T) were obtained in the same way as for the He I 501.6 nm line, applying the corresponding "optically thick" results of Srivastava and Ghosh. The results are listed in Table 1. The data are arranged according to increasing excitation energies of the selected spectral lines.

The rather large scatter of the listed N_e and T data characterize, to some extent, the accuracy of the N_e and T determination. On the other hand, the agreement between results obtained on the basis of the 501.6 nm line and the lines originating from the levels with $n=4$ is satisfactory. These levels are very close to the ionization limit ($\Delta E=0.85$ eV), and according to the collisional–radiative model, at electron densities of the order of $10^{20}\,\mathrm{m}^{-3}$, the Saha-decrements are very close

Table 1. Temperature and electron density values obtained on the basis of the collisional–radiative model after Srivastava and Ghosh [12] and on measured intensities of selected He I spectral lines. The results correspond the center of the discharge volume at a pressure of 107 hPa

Wavelength [nm]	Level	Level population [m^{-3}]	Electron density [m^{-3}]	Temperature [K]
706.5	3^3S	7.9×10^{14}	7.0×10^{19}	14880
728.1	3^1S	3.6×10^{14}	3.1×10^{19}	14400
587.6	3^3D	7.4×10^{13}	10.0×10^{19}	15300
667.8	3^1D	1.6×10^{14}	3.1×10^{19}	14400
501.6	3^1P^0	1.8×10^{14}	5.8×10^{19}	14780
447.1	4^3D	8.8×10^{12}	7.3×10^{19}	14910
492.2	4^1D	2.9×10^{13}	6.6×10^{19}	14850

to the value of 1. The population of these levels is therefore much less sensitive to the rate coefficients for the various elementary processes on which the results of the collisional–radiative model are based.

5. Conclusions

The results obtained in this work show that the most important parameters of the He plasma (electron density and electron temperature) depend strongly on the gas pressure. With decreasing pressure the electron temperature, as well as the electron density of the plasma, increase. The dependences, however, are slightly different for different plasma regions (different distances from the ceramic surface). Consequently, the gradients of these parameters change significantly with the pressure. For pressures in the range 2×10^3–5×10^3 Pa, the plasma around the center of the discharge volume is nearly homogeneous. This plasma region (about two-thirds of the whole volume) is therefore very convenient for possible applications of the radiation emitted from the source as well as for spectroscopical studies of spectral lines at electron densities below $10^{21}\,m^{-3}$.

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