PERGAMON

Journal of Quantitative Spectroscopy & Radiative Transfer 67 (2000) 217–225

Journal of Quantitative Spectroscopy & Radiative Transfer

www.elsevier.com/locate/jqsrt

Spectroscopic and electric probe measurements of plasma parameters in the negative glow region of helium discharge plasma

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Received 28 July 1998

Abstract

The essential plasma parameters, i.e., electron temperature, T_e electron density, n_e and ion temperature, T_i, have been measured in the negative glow (NG) region of a helium cold-cathode discharge plasma as a function of the filler gas pressure. For the determination of these parameters two different techniques have been used throughout this work. Spectroscopic technique depending on the line intensity ratio of He(I) resonance line at 3888.65 Å and He(II) ionized line at 4686 Å, besides the width and profile of the working heluim gas, is the first one, while electrical single probe technique depending on the voltage–current characteristics of the plasma is the second one. By this second technique the experimental data of the floating potential, V_f, and the plasma potential, V_s, were used to define the negative glow region. Comparison between the results of both techniques revealed a strong agreement of the measured values of T_e, besides a fairly good agreement of the measured values of n_e. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

DC cold-cathode glow discharges have been studied for many years. Recently, efforts have been intensified to understand the glow discharge regions, (cathode fall, negative glow and positive column regions, respectively), which can be created from the interaction mechanism of the electron beam with the working gas. Some of these efforts have included experimental treatments [1–4]. The electron beam source is produced mainly from the cathode surface and may be pulled from the plasma sheath which is adjacent to the cathode surface. For DC-cathode plasma, the main source of the electron beam is the primary electron released from the cathode by ion bombardment. The

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PII: S0022-4073(99)00209-5

emitted electrons have been accelerated afterwards by the potential difference which is equal to the cathode fall. Therefore, these electrons have gained energy to excite the gas atoms producing the negative glow [5–7]. There is a good correlation between the length of the negative glow and the range of accelerated electrons [8]. A study of the electron beam parameters in the normal glow discharge can clarify the processes of the different interactions and regions, the negative glow region is one of them.

For the present investigation, optical emission spectroscopic and Langmuir probe techniques are used to characterize the glow discharge regions which take place in the plasma. Spectroscopically, the visible light emitted by the discharge plasma column is often used for diagnostic purposes, however, due to a lack of thermal equilibrium, interpretation of the absolute intensities of spectral lines or molecular bands is not trivial [9]. The essential plasma parameters, i.e. the electron and ion densities, and the electron and ion temperatures, could be achieved by these techniques at the edge and inside of negative glow region. The spectroscopic measurements depend upon the intensity ratios, widths and profiles of neutral and ionized He-lines. Brenning and others have discussed the possibility of determining electron temperature from the relative intensities of spectral lines in low-density plasmas. It is concluded that most lines can only be used at very low densities ($N_e < 2 \times 10^{16}\ \mathrm{m}^{-3}$) because the line intensities are highly influenced by secondary processes [10,11]. While the Langmuir probe measurements depending on the current–volt characteristic of single electric probe have been used for measuring the plasma parameters and defining the negative glow region from the experimental data of the floating potential, V_f, and the plasma potential, V_s.

2. The experimental system

2.1. Source

Experiments were carried out in a flowing gas discharge tube made of Pyrex 20 cm long and 20 cm diameter where a pair of aluminum electrodes are sealed at its ends, Fig. 1. Helium gas was made to flow into one end of the discharge tube through a needle-valve until the working gas pressure is achieved. This gas was exhausted by a rotary pump. The discharge was run from a regulated DC-power supply with a rheostat ballast by a positive potential applying to the anode; the cathode was earthen.

2.2. Monochromator device and photomultiply tube

The spectroscopic light source for the present experiment is the DC glow discharge plasma described previously. Light was collected from the discharge passed via an entrance slit of the monochromator device. In order to obtain the necessary high resolution, 1.5 m THR1500 monochromator device was used. The monochromator was fitted with a plane square, holographic grating with $80 \times 110\ \mathrm{mm}^2$ width-height and 1800 line/mm. The resolving power yielded while the grating operated in a single pass is 175,000. The reciprocal linear dispersion is nearly 2.6 Å/mm in the wavelength range between 2000 and 9000 Å. An entrance slit of 5 mm width was used. The monochromator outputs were focused onto a highly sensitive photomultiplier RCA IP21 coupled with IBM computer through ISA Divsion JOBIN-YVON spectrolink.

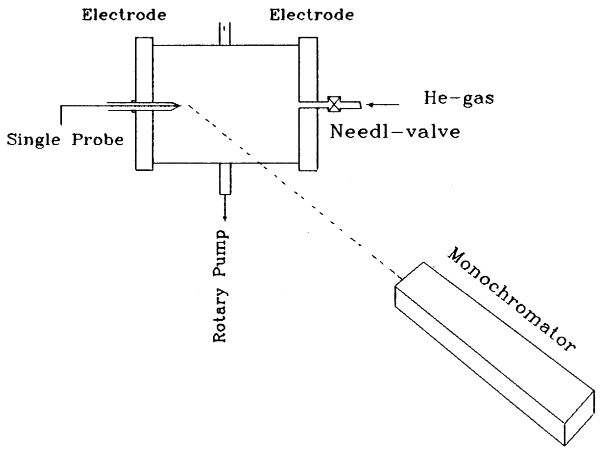

Fig. 1. Glow discharge plasma experiment assembly.

2.3. Single electric probe

A single electric probe was constructed from 0.5 mm diameter tungsten wire encapsulated in a glass sleeve. The body of the probe sites in the center of the discharge tube through the earthed electrode. The probe could be moved along the axis of the tube by means of an external tool; the tube wall was marked with graduations to define the probe position. DC-power supply was applied for probe potential.

3. Experimental results and discussions

The measurements were taken at the edge and inside of negative glow plasma region at 0.4, 0.6 and 0.8 Torr. helium gas pressures for mean discharge current densities of 0.095, 0.121 and 0.146 mA/cm^2, respectively. The measured potential differences between the discharge electrodes were 300, 260 and 220 V, respectively, with the pressures. These measurements could be applied to two different techniques which are used to determine the electron temperature, T_e electron density, n_e and the ion temperature, T_i. The first is spectroscopic measurement technique, and second a single electric probe technique.

3.1. Spectroscopic technique

3.1.1. Ion temperature

It has been shown that the experimental spectral line profiles have to be corrected for contributions to broadening. These contributions arise from the Doppler broadening, collisional broadening, and broadening influences caused by instrumental slit widths. Our measurements were performed using a low-density glow discharge plasma. The discharge was operated in helium at a filer gas pressure of 0.2–0.8 Torr and at currents between 30 and 46 mA. Under these conditions

Table 1
Experimental He (I) and He (II) full half-widths with the calculated values of ion temperature, T_i, at different gas pressures

Pressure (Torr)	Line at 3888.65 Å of He (I)		Line at 4686 Å of He (II)	
	$\Delta\lambda_{1/2}$ (Å)	T_i (eV)	$\Delta\lambda_{1/2}$ (Å)	T_i (eV)
0.8	0.382	6.49	0.448	6.150
0.6	0.376	6.29	0.453	6.288
0.4	0.374	6.22	0.418	5.354

collisional broadening are small enough to be negligible [12,13]. The instrumental profile of the monochromator was determined experimentally by investigating the width of the 6328 Å emission line of He–Ne laser. The laser line had a full-width at half-maximum intensity (FWHM) of less than 0.05 Å. So it is easy to conclude that, the Doppler broadening makes the largest contribution to the experimental line width.

As we knew the instrumental width, it was possible to deduce the ion temperature from Doppler line broadening [14,15]. Since the emitting atoms and ions in the plasma possess random velocities, spectral lines will be broadened due to the Doppler effect. If the random motion is of thermal origin, the Doppler profiles are Gaussian (in the absence of any other broadening mechanism) with half-width (at half-maximum intensity) given by [16]

$$\Delta\nu_D = \left[\frac{2kT_i\nu_0^2}{Mc^2}\right]^{1/2}, \tag{1}$$

where T_i is the temperature of the emitting ions and M is their mass.

The experimentally determined full half-widths of He (I) resonance line at 3888.65 Å and He (II) line at 4686 Å, with the calculated values of ion temperature at different gas pressures, are given in Table 1.

3.1.2. Electron temperature and denisty

Many of the spectroscopic diagnostic methods of measuring electron temperature and density are based on the theoretical plasma models [17]. It should be mentioned that, for the experimental conditions here reported, the electron density inferred from the probe measurements gives $n_e \approx 10^{10}\ \mathrm{cm}^{-3}$. This suggested that the so-called steady-state corona model should be used in studying the plasma formed in the glow discharge.

The corona mode, i.e. the collisional ionization (or excitation) is balanced by radiative recombination (or spontaneous decay), was developed for plasmas of low electron density. For hydrogen and hydrogen-like ions, the electron density may be expressed using the following inequality [17]:

$$n_e < 5.6\times10^8(z+1)^6T_e^{1/2}\exp\left[\frac{1.162\times10^3(z+1)^2}{T_e}\right], \tag{2}$$

where T_e is the electron temperature.

Table 2
The electron temperature, T_e and density, n_e values for negative glow region of He glow discharge as a function of the He pressure

Pressure (Torr)	T_e (eV)	$n_e < 10^{13}$ cm^{-3}
0.8	5.723	3.962
0.6	5.839	3.997
0.4	6.287	4.127

Accurate spectroscopic measurements of T_e, under the steady-state corona model, could be obtained from the ratio of ion and neutral line intensities. In the present study, T_e can be obtained from the ratio of the ion and neutral line intensities (i.e. 4686 He (II)/3888.65 Å He (I) ratio) using the following relation [14]

$$\frac{I'}{I} = \frac{f'g'\lambda^3}{fg\lambda'^3}\exp\left[\frac{E_\infty - E' - E_\infty + E}{kT_e}\right]\frac{S}{\alpha}, \tag{3}$$

where I, λ, g, and f are total intensity, wavelength, statistical weight (of the lower state of the line), and absorption oscillator strength, respectively, of the neutral line and E, E_∞ are its excitation and ionization energy. The primed quantities refer to the ionized line. S and α are collisional ionization and radiative recombination coefficients given by [17]

$$S(T_e, z, g) = 2.34 \times 10^{-7}\,\frac{\zeta T_e^{1/4}}{[\xi(z,g)]^{7/4}}\exp\left[-\frac{\chi(z,g)}{kT_e}\right] \tag{4}$$

and

$$\alpha(T_e, z, g) = 2.05 \times 10^{-12}\,\frac{\chi(z-1,g)}{T_e^{1/2}}, \tag{5}$$

where ξ is the number of outer electrons, T_e is in K, and $\chi(z,g)$ is the ionization potential of the ion of charge z in its ground level [17].

The results of T_e obtained using Eqs. (3)–(5) as a function of the gas pressure in helium glow discharge in the negative glow region are given in Table 2. Values of T_e were varied from nearly 5–7 eV in the pressure range of 0.4–0.8 Torr. The present measurements show that, T_e values decrease as the gas pressure increase. This can be explained as, at low gas pressure, the electron–neutral particles collision frequency is small and the mean free path is high. While at high pressures the collision frequency increases and hence, the loss of electron energy is high, thus T_e decreases [18].

The electron density, n_e may be estimated using inequality (2) with the help of the values of T_e which was determined previously. Table 2 includes the values of electron density, n_e as a function of gas pressure. The present results indicate that the electron density increases by increasing the gas pressure. This may be attributed to the increase in the number of electron–atom collisions, and this consequently increases the ionization rate [18].

3.2. Electrical single-probe technique

The used probe made of tungsten wire 0.5 mm radius gave the I–V characteristic curves. The analysis of these curves showed that the electron temperature could be derived from Eq. (6) [19]

$$\ln i_e = (e/kT_e)V_p + \ln A_p j_0 - (e/kT_e)V_s, \tag{6}$$

where V_p is the probe potential, V_s is the space potential, A_p is the effective area of probe-surface-exposed plasma, i_e is the electron probe current and j_0 is the random electron current density. By plotting $\ln i_e$ against the probe potential, V_p one can easily estimate the electron temperature, T_e.

The plasma electron density was determined from the saturation electron probe current at the space potential by Eq. (7) [20]

$$i_e = i_{es}\exp(\eta) \quad (\eta \le 0) \tag{7}$$

and $\eta = e(V_p - V_s)/kT_e$. When the probe potential, V_p, approaches to the space potential, V_s, the saturation electron current becomes

$$i_{es} = A_p e n_e (kT_e/2\pi\, m_e)^{1/2} \quad (\eta = 0). \tag{8}$$

All probe measurements were carried out on the electrons when the probe was located at different axial positions inside 20 mm length of the plasma, from the cathode surface to the negative glow (NG) region. Considering that there is a weak plasma in equilibrium state and it covers the

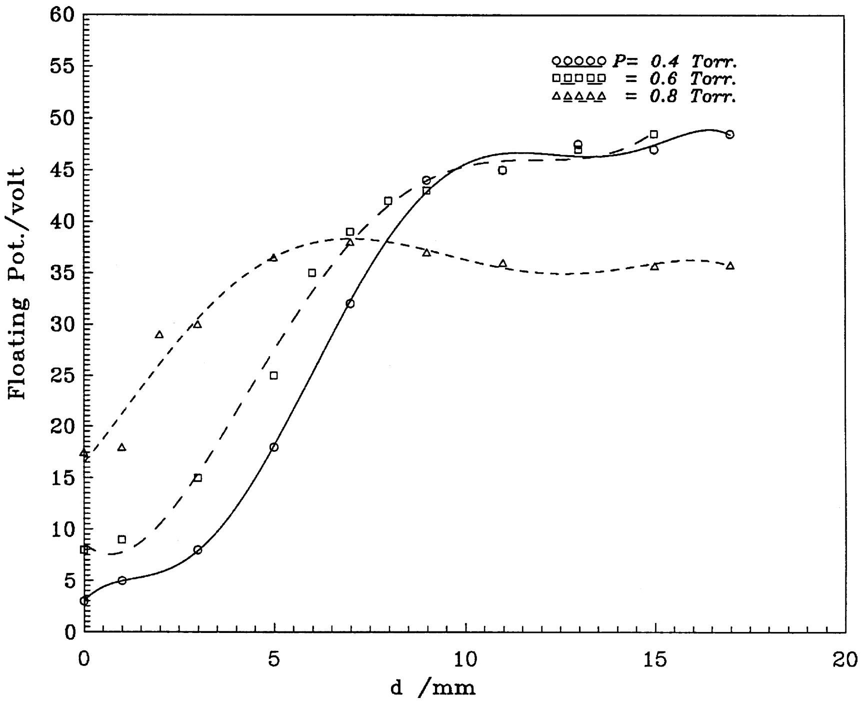

Fig. 2. Floating potential vs. distance from the cathode surface to inside the negative glow region.

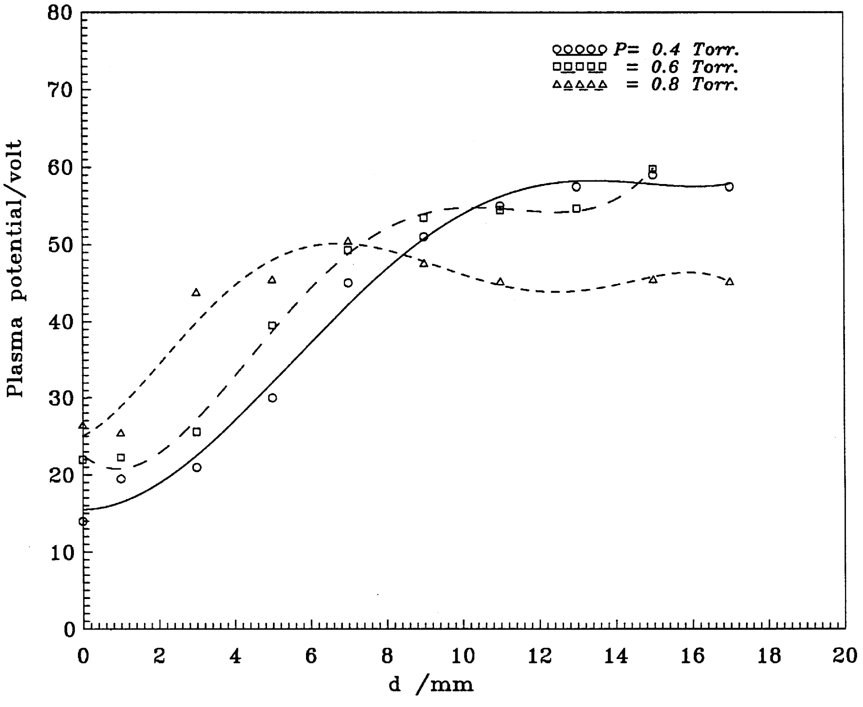

Fig. 3. Plasma potential vs. distance from the cathode surface to inside negative glow region.

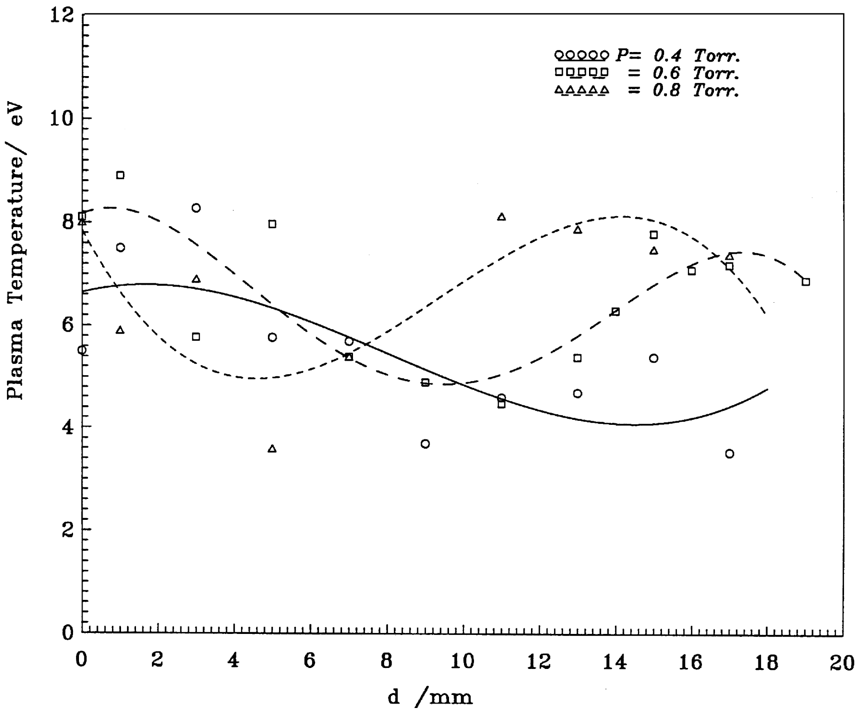

Fig. 4. Plasma temperature vs. distance from the cathode surface to inside negative glow region.

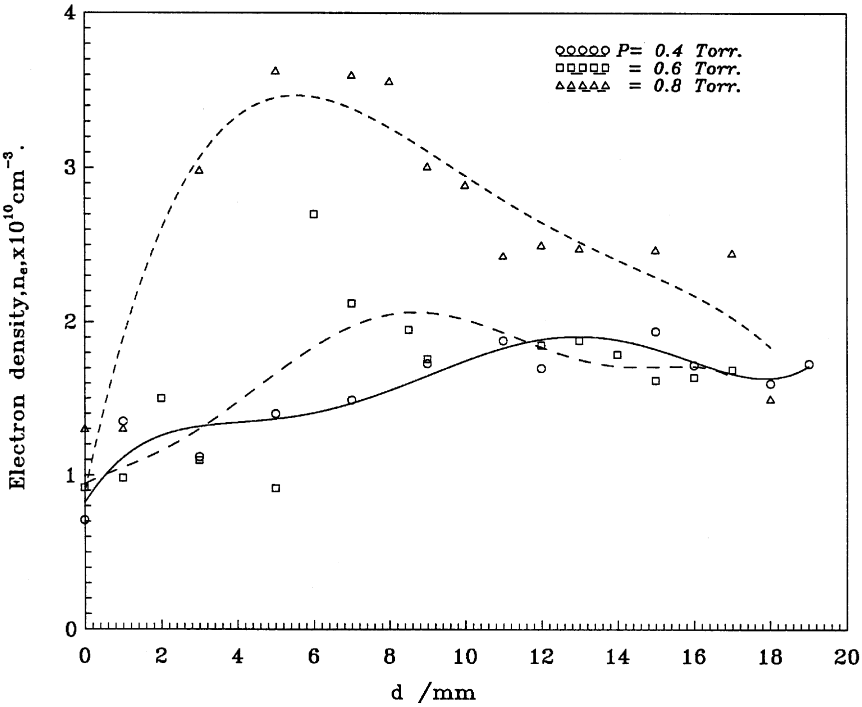

Fig. 5. Electron density vs. distance from the cathode surface to inside negative glow region.

mentioned length, the floating potential and plasma spatial potential profiles can be deduced from the single probe characteristics. The floating potential, V_f, is the probe potential at which the electron and ion currents are equal, while the plasma potential (space potential), V_s, is the potential of the point of interaction between the electron saturation current line and the line of the increasing electron current of the $\ln(I)$–V curve.

By both floating and plasma potential profiles we were able to identify plasma regions inside the length of 20 mm from the cathode surface, the negative glow, NG, region is one of them. Figs. 2 and 3 and show that the NG region takes places in the discharge tube at distances of 5, 7 and 10 mm away from the cathode surface at pressures of 0.8, 0.6 and 0.4 torr, respectively. It has also been noted that both the floating and plasma potential points are nearly convergent inside the lighted regions, such as the negative glow, NG, region. This is because of the accumulation of the majority electrons inside these regions. The collected electrons are subjected to electron–atom collision (inelastic collision) and therefore loosing most of their energies.

For optimum conditions of DC-glow discharge, variation of the electron temperature, T_e and density, n_e to the plasma column obtained, is shown in Figs. 4 and 5. Electron temperature, T_e was varied in the range of 4.0–8.0 eV at pressure values of 0.8–0.4 Torr. Meanwhile, the electron density, n_e takes the values of 0.9–3.5 × 10^{10} cm^{-3} for the mentioned pressures.

4. Conclusion

An important point of view is the comparison between the results of the measured electron temperature, T_e and electron density, n_e from the two techniques used. It is a point of interest to conclude that, a strong agreement exists between the measured values of, T_e while there is a fair agreement of the measured values of, n_e. The fair agreement of, n_e is because of the shortcoming of the spectroscopic methods for determining the electron density, n_e.

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