

Spectroscopic Study of Argon DC Glow Discharge

Abdou A. Garamoon, Ahmed Samir, Farouk Fahmy Elakshar, A. Nosair, and Eizaldeen F. Kotp

Abstract—In this paper, emission spectra of both positive column (PC) and negative glow (NG) regions of the dc glow discharge have been measured at different pressures and currents. The intensity of the lines in the NG is in the order of five times of that corresponding lines' intensity in the PC region. It is found that the line intensity increases linearly with the discharge current, while it increases as P^α with the gas pressure. The electron temperature T_e has been estimated using the line-to-line-intensity-ratio technique. It is found that T_e derived by this technique generally decreases with the pressure. Also, T_e in NG region is about 3/2 of that in the PC.

Index Terms—Diagnostics, electron temperature, gas discharge, plasma, probes, spectroscopy.

I. INTRODUCTION

THE OBJECTIVE of plasma diagnostics is to obtain information about the state of the plasma by means of different experimental techniques. Knowledge of plasma characteristics is required to understand fully the effects of the different physical processes taking place in the plasma and to deduce from them its properties. These diagnostics includes electric probes and optical emission spectroscopy.

Usually, only probes are used routinely for measuring the temperature and density of electrons and ions. However, in magnetized or depositing plasmas in particular, the interpretation of probe characteristics is difficult and can lead to erroneous results [1]. Optical methods such as emission, absorption, laser scattering, or fluorescence spectrometry are proven techniques for probing various parts of the plasma without disturbing its state and composition [2]. Among these techniques, there is the optical emission spectroscopy [3]. This technique is based on the measurement of the optical radiation emitted from the plasma as it reflects the properties of the plasma in the immediate environment of atomic, molecular, and ionic radiators [4].

The radiation is the result of electron or ion interaction with other particles in the plasma. Because of their high velocity, electron interactions tend to dominate the collisional excitation

and ionization processes. Three electron transitions may occur during these interactions: bound-bound transitions; bound-free transitions; and free-free transitions. The light emitted as a result of these transitions forms line, band, or continuous spectra.

Atoms and ions of the working gas and trace impurities emit radiation when transitions of electrons occur between the various energy levels of the atomic system. The radiation is in the form of narrow spectral lines, unlike the continua of free-electron radiation such as bremsstrahlung [5]. Four plasma models were suggested by McWhirter [6], which are dependent on the mechanism of electron interaction.

These are the local-thermal-equilibrium (LTE) model, the steady-state corona model, the time-dependent corona model, and the collisional radiative model. The methods used to measure the plasma parameters depend on the plasma model. Three methods are available for electron temperature measurement, these are:

- 1) the ratio of two lines' intensity;
- 2) the ratio of a line to continuum intensity;
- 3) the ratio of two parts of continuum intensities.

The first method will be used in this paper for the estimation of the mean electron temperature in the argon dc glow discharge [7]–[11].

II. EXPERIMENTAL SETUP

The discharge cell consists of two movable parallel electrodes enclosed in a pyrex tube. The two electrodes were made of copper–brass disks of 3.0-cm diameter, while the pyrex glass tube was 4 cm in diameter. The tube was pumped down by a vacuum system to base pressure of 10^{-4} torr.

A continuous dynamic flow of argon gas (of purity 98%) was let in the system through a needle valve at the desired pressure. Fig. 1 shows the circuit for measuring the current–voltage (I – V) characteristics of the discharge [12]. Digital storage oscilloscope (DSO) (type HM-407) was used to measure the I – V curve of the discharge. The voltage across the discharge tube has been measured through the X -channel of the oscilloscope using potential divider 10:1. The current has been measured through the Y -channel of the oscilloscope by measuring the voltage drop across resistance of $200\ \Omega$ connected in series with the discharge tube. The data stored in the DSO was then fed and stored into personal computer (PC).

McPherson scanning monochromator [model 270] with 35-cm focal length and having a diffraction grating of 1200 grooves/mm has been used to scan the spectral lines. The resolution of this monochromator is less than $0.2\ \text{\AA}$. The intensity of the light has been measured using a photomultiplier tube (type 9558QB). The output of the photomultiplier was recorded using a digital multimeter (type GDM-8145).

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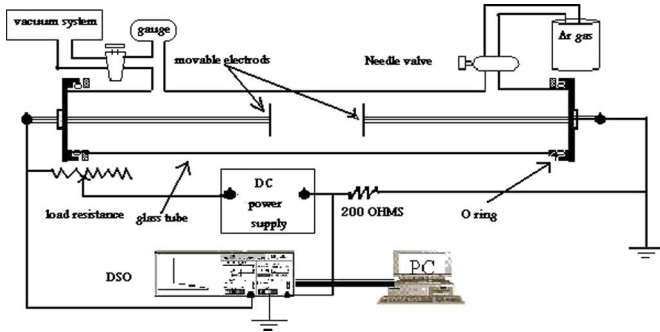


Fig. 1. Schematic diagram of the experiment.

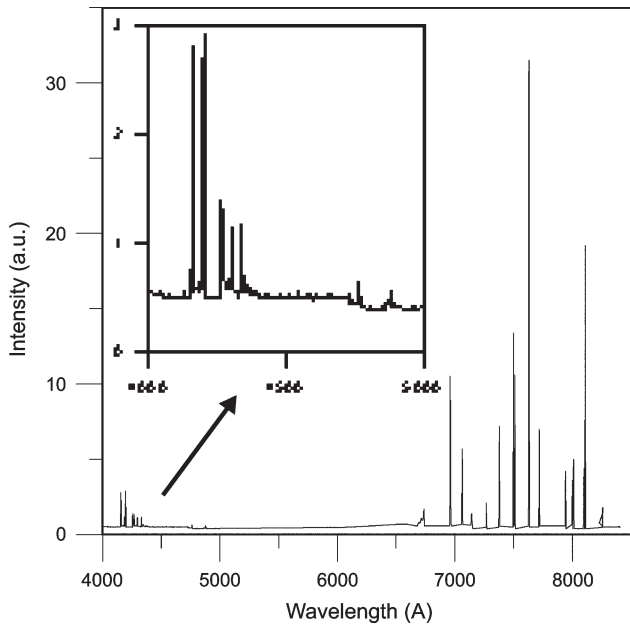


Fig. 2. Emission spectrum of PC at 2.25 torr and $I = 10$ mA.

III. RESULTS AND DISCUSSION

Figs. 2 and 3 show the emission spectrum of argon gas in the positive-column (PC) and negative-glow (NG) regions, respectively.

All lines appeared in the spectrum have been identified as Ar and Ar^+ spectra.

Comparison between Figs. 2 and 3 show the following results.

- 1) Intensity of lines in NG region is much higher than that in PC region.
- 2) Intensity of the lines in the long wavelength range (7000–8000 Å) in NG region is in the order of two times of that corresponding intensity of lines in the PC region. At shorter wavelengths (4000–5000 Å), however, the intensity of lines in the NG region is in the order of five times of the corresponding intensity of the lines in the PC region.
- 3) Lines of Ar^+ appear clearly in the NG, while they hardly appear in the PC region.

The general increase of the intensity of the lines in the NG region can be attributed to the increase in the rate of exciting

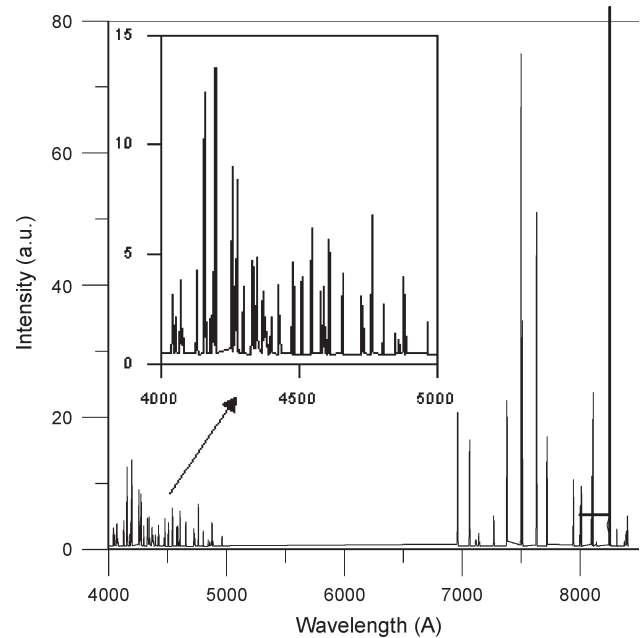


Fig. 3. Emission spectrum of NG at $p = 2.25$ torr and $I = 10$ mA.

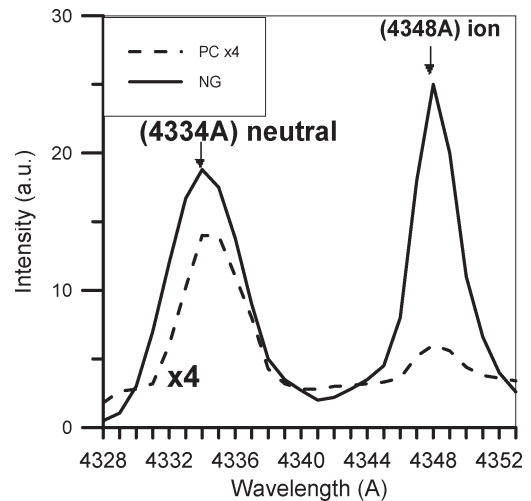


Fig. 4. Emission spectrum from PC and NG of two lines 4334 Å from the neutral Ar atom and 4348 Å from Ar^+ ion.

collisions due to both of the higher electron temperature and higher electron density in NG region rather than those in PC. This discussion can explain why the ratio of the intensities of the lines in NG to that in PC is much higher at short wavelengths than those at long wavelengths.

A comparison between the intensities of the two lines of neutral atom Ar and that of the singly ionized ion Ar^+ in PC and NG regions has been represented in Fig. 4.

The intensity of the lines in PC has been multiplied by a factor of four, in order to be comparable with that in the NG. In NG region, the intensity of the line 4348 Å is higher than that of the line 4334 Å. In the PC region, however, the line 4348 Å hardly appears and its intensity is much lower than the intensity of the line 4334 Å. Since ion density and the mean electron energy in NG is much higher than that in PC, therefore, the probability of exciting collisions of electrons with Ar^+ in

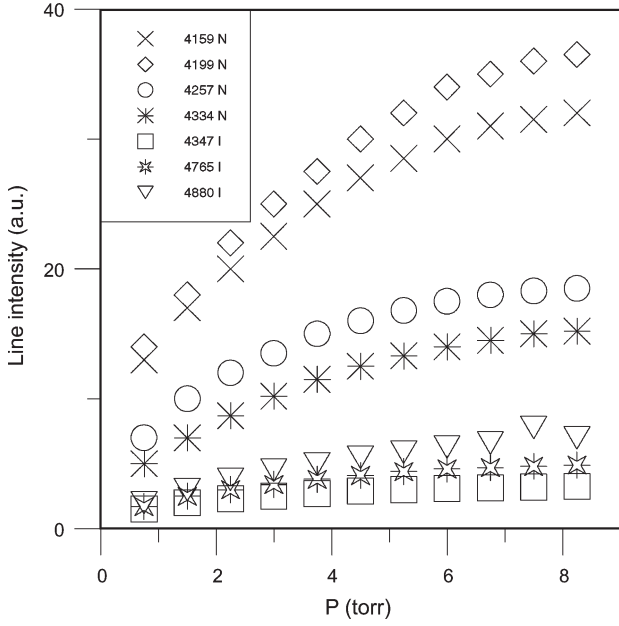


Fig. 5. Line intensity (a.u.) of four lines from Ar atom and three lines from Ar^+ ion as a function of gas pressure in the PC region, $I = 20$ mA.

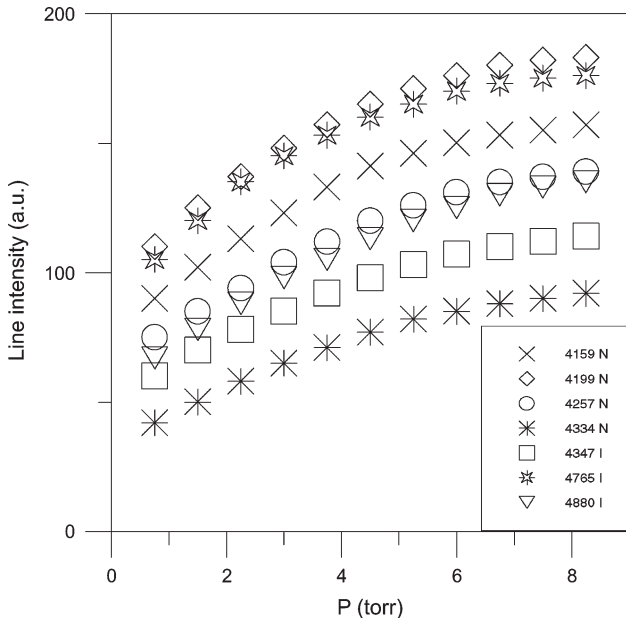


Fig. 6. Line intensity (a.u.) of four lines from Ar atom and three lines from Ar^+ ion as a function of gas pressure in the NG region, $I = 20$ mA.

NG region is higher than that in PC. Consequently, most of Ar^+ lines appear clearly in NG region and hardly appear in PC region.

Figs. 5 and 6 represent the line intensity of some lines as a function of the gas pressure in PC and NG, where intensity increases by increasing the gas pressure (p). The line intensity I_{pq} can be expressed in the form [13]

$$I_{pq} = N_e N \langle Q_{pq}(\nu_e) \nu_e \rangle \quad (1)$$

where ν_e is the electron velocity $\{\nu_e = (2kT_e/m_e)^{1/2}\}$, $Q_{pq}(\nu_e)$ is the excitation cross section for the p-q transition averaged over the electron energy distribution, N_e is the elec-

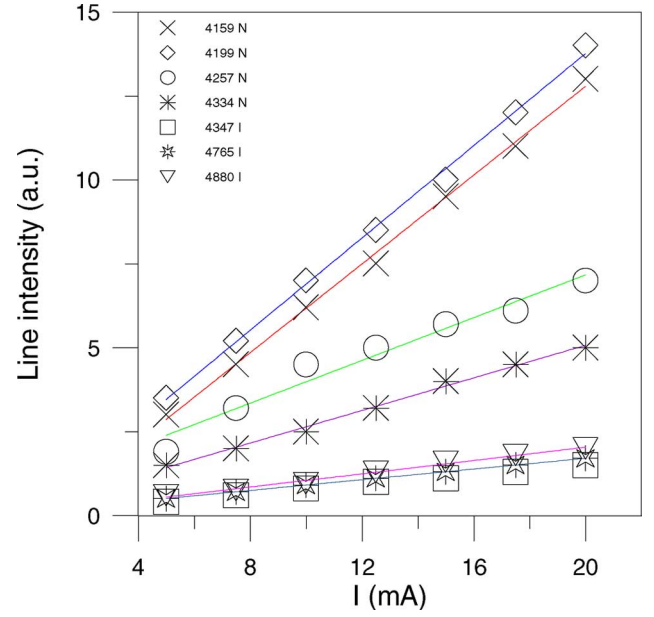


Fig. 7. Line intensity (a.u.) of four lines from Ar atom and three lines from Ar^+ ion as a function of current in PC region, $P = 0.75$ torr.

tron density, and N is the density of Ar atoms or the density of Ar^+ ions.

As the gas pressure increases: 1) N_e and N increase, consequently the lines' intensity increases. 2) T_e decreases and, hence, the rate coefficient of electron exciting collision $\langle Q_{pq}(\nu_e) \nu_e \rangle$ decreases; consequently, the intensity of the lines decreases, whereas $\nu_e \sim T_e^{1/2}$. In the range of p of 0.75–12 torr that has been used, the first factor is more effective than the second one. Therefore, the intensity of the lines increases by increasing the gas pressure, where the intensity of the lines has been found to be proportional to p^α , where α is constant, which varies between 0.2–0.5, depending on the wavelength.

Figs. 6 and 7 show the variations of the line intensities as a function of the discharge current I .

It can be noticed that the lines' intensity increases linearly by increasing the discharge current, i.e., $I_{pq} \sim I$, in general. This can be attributed to the increase in the electron density N_e , which is a linear function of the current, where $I_{pq} = cI$ (mA), where c is a constant, which is found to vary between 0.07 to 0.7 in PC and 1.2 to 3.8 in NG and depends on the wavelength.

A. Electron Temperature by Optical-Emission-Spectroscopy Technique

Determination of T_e using optical-emission-spectroscopy technique by estimating the ratio of the intensity of two lines has been adopted here in this paper. For high accuracy, it is desirable to choose two spectral lines, whereas the ratio of the relative intensity of the two lines is a strong function of T_e . This will be the case if the difference between the transition-energy levels of the two lines is large enough. However, for neutral atoms, the greatest attainable energy difference yields a minimum uncertainty in temperature of 70% for argon gas in the range of 0.5–1.5 eV [14]. The accuracy may be improved

somewhat by measuring several pairs of spectral lines and averaging the resulting temperatures. However, this rather time-consuming technique is only partially successful in reducing the experimental uncertainty. A larger energy difference can be obtained if one of the transitions occurs in singly ionized atom and the other occurs in a neutral atom. Therefore, the relative intensity of argon neutral atom (4159 and 4259 Å) and argon singly ionized atom Ar⁺ (4348, 4765, and 4880 Å) have been measured at different pressures and discharge currents in both NG and PC regions.

In the first trials in this paper, T_e has been determined assuming LTE model. Using the ratio of two lines' intensity, T_e can be expressed in the form

$$kT_e = \frac{E' - E}{\ln(I\lambda^3 g' f' / I' \lambda'^3 g f)} \quad (2)$$

where I , λ , g , and f are the total intensity, wavelength, statistical weight, and absorption oscillator strength, respectively, of one line and E is its excitation energy. The corresponding quantities for the other line are I' , λ' , g' , f' , and E' . The values of the above parameters have been taken from [15]. T_e values obtained by this method were in the range of 0.3–0.9 eV. These results are much smaller than the measurements obtained by the electric single and double probes. This may be attributed to the fact that the plasma density is so low that the criterion of LTE model is not valid, i.e., that

$$N_e \geq 1.6 \times 10^{12} T_e^{1/2} X(p, q)^3 \text{ cm}^{-3}. \quad (3)$$

On the other hand, the criterion of the steady-state corona model, i.e., that

$$N_e < 5.6 \times 10^8 (z + 1)^6 T_e^{1/2} \exp\left(\frac{1.16 \times 10^3 (z + 1)^2}{T_e}\right) \quad (4)$$

is valid in this paper. Consequently, steady-state corona model has been assumed here to estimate T_e . The ratio of two lines' intensity T_e is expressed in the form

$$\frac{I'}{I} = \frac{f' g' \lambda^3}{f g \lambda'^3} \exp\left(\frac{E'_\infty - E' - E_\infty + E}{kT_e}\right) \frac{S}{\alpha} \quad (5)$$

where

$$\frac{\alpha}{S} = (7.87 \times 10^{-9}) E_\infty'^2 \left(\frac{E'_\infty}{kT_e}\right)^{3/4} \exp\left(\frac{E'_\infty}{kT_e}\right). \quad (6)$$

Eliminating S/α from (5), therefore

$$kT_e = \left[(7.87 \times 10^{-9}) E_\infty'^{7/4} \frac{f g I' \lambda^3}{f' g' I \lambda'^3} \exp\left(\frac{E' E_\infty - E}{kT_e}\right) \right]^{4/3}. \quad (7)$$

Values of the parameters used in (7) have been taken from [15] and is tabulated in Table I.

Equation (7) shows that, T_e cannot be written as an explicit function of the ratio of lines' intensity [i.e., $T_e \neq f(I'/I)$]. The

TABLE I
RATIOS OF THE TWO LINES' INTENSITIES I'/I , ONE FROM SINGLE IONIZED ATOM AND THE OTHER FROM NEUTRAL ATOM, HAVE BEEN ESTIMATED FOR SIX PAIRS OF LINES (4159/4348, 4159/4765, 4159/4880, 4259/4348, 4259/4765, AND 4259/4880)

$\lambda(\text{\AA})$	Transition	E(eV)	$J-J'$	f
4158.6	1S ₂ -3P ₆	14.47	2-2	0.0017
4259.4	1S ₂ -3P ₁	14.67	1-0	0.0022
4348.1	3P ⁴ 4S- 3P ⁴ (3P)4P [⁴ P- ⁴ D ^o]	19.41	5/2-7/2	0.4300
4764.9	3P ⁴ 4S- 3P ⁴ (3P)4P [² P- ² D ^o]	19.78	1/2-3/2	0.3700
4879.9	3P ⁴ 4S- 3P ⁴ (3P)4P [² P- ² P ^o]	19.60	3/2-5/2	0.3500

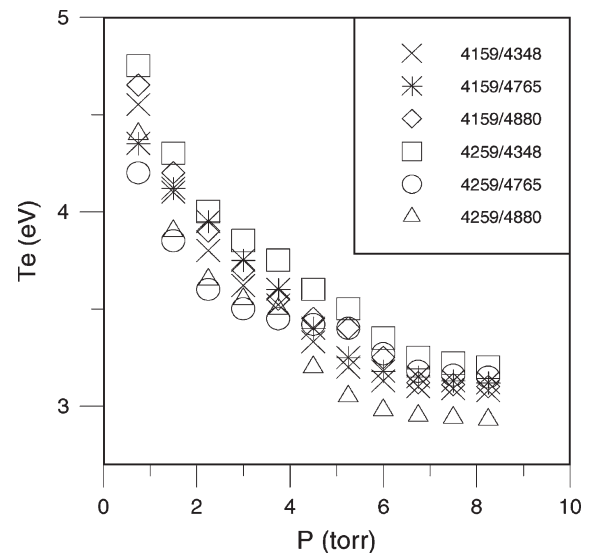


Fig. 8. Values of electron temperature as a function of gas pressure in the PC, using emission-spectroscopy technique with different line ratios.

implicit function [$T_e = f(I'/I, T_e)$] can be solved numerically. Successive iteration has been carried out to solve (7). The guess point has been chosen using single- and double-probe measurements to accelerate the iteration process. The results of these process is shown in Figs. 8 and 9, where the derived T_e is plotted as a function of the pressure in two regions of the glow discharge.

The results in these two figures indicate a reasonable agreement of the estimated values of T_e and also that T_e has the same trend of behavior with pressure using the any pairs of lines, i.e., T_e decreases by increasing the gas pressure (p).

Since the kinetic energy of an electron can be expressed as $mv^2/2 = eE\lambda_e$, where λ_e is the electron mean free path, so T_e is proportional to λ_e and, hence, inversely proportional to p .

Also, that T_e depends to a great extent on the chosen pairs of lines that has been used in the estimation of T_e that the difference in T_e can reach up to 25%. It is worth mentioning here that the electron energy distribution in the PC region has been found to be Maxwellian, where it was checked by electric-probe measurements [16] while it is not in NG region, where more than one group of electrons with each group having a Maxwellian distribution separately has been found (to be

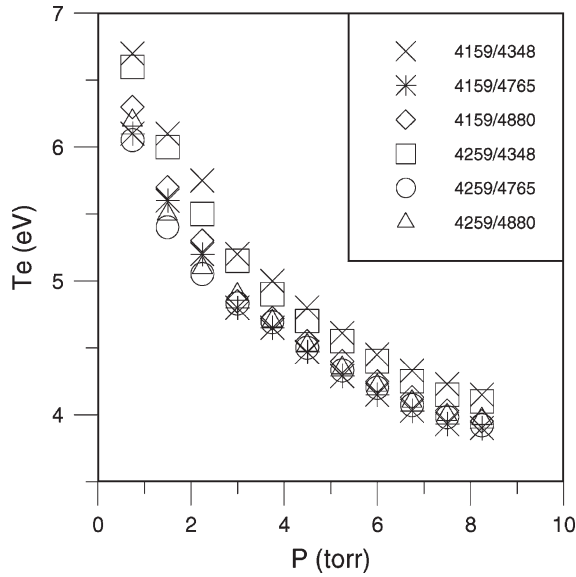


Fig. 9. Values of electron temperature as a function of gas pressure in the NG, using emission-spectroscopy technique with different line ratios.

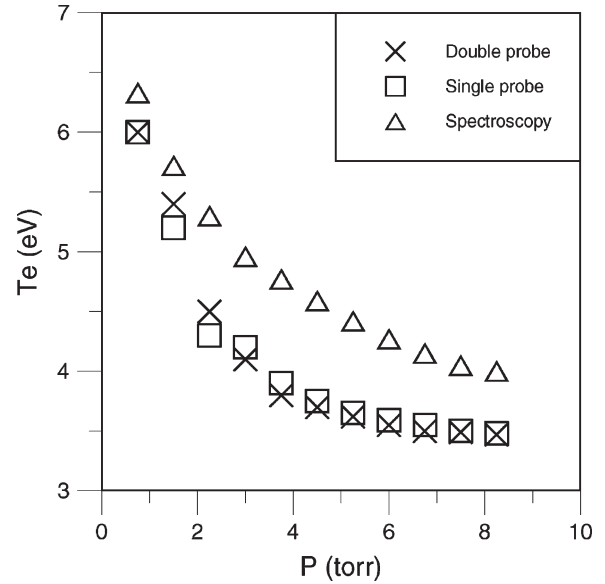


Fig. 11. Values of electron temperature as a function of gas pressure measured by different techniques in NG.

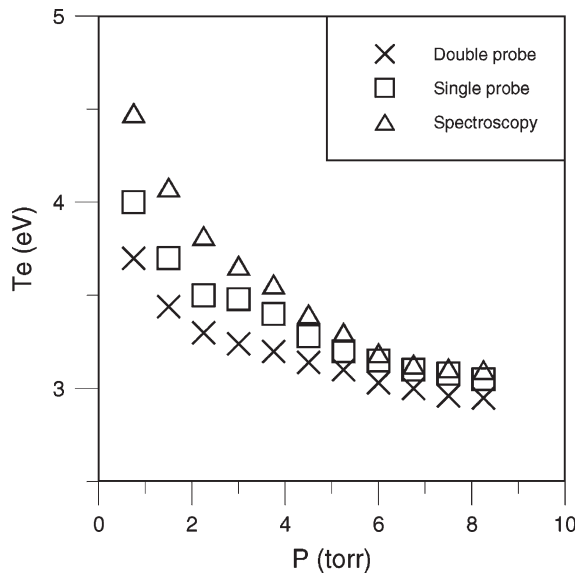


Fig. 10. Values of electron temperature as a function of gas pressure measured by different techniques in PC.

published later). Due to this reason, results in the NG region has to be looked upon as it reflects only the general trend of T_e with pressure.

Also, it can be noticed that the electron temperature in the NG region is about 3/2 of that in the PC.

B. Comparison Between the Three Techniques Used to Measure T_e

Figs. 10 and 11 represent values of T_e as a function of the gas pressure in PC and NG regions, respectively, using the average values measured by the three techniques, i.e., single-probe, double-probe [11], and optical-emission-spectroscopy techniques.

A fair agreement between the three techniques is observed especially in the general trend of variation of temperature with pressure [12].

Also, Figs. 10 and 11 prove that the agreement between optical emission spectroscopy and the probes techniques in the PC region is much more closer than that in the NG region where up to 30% difference between the results obtained by spectroscopic and those by probe techniques can be observed. This may be attributed to the fact that the distribution of electrons in the NG region is non-Maxwellian.

IV. CONCLUSION

A comprehensive experimental study for the optical emission from the NG and PC of the dc glow discharge in argon gas has been performed. The line intensities of different lines have been measured as a function of gas pressure and the discharge current. The intensity of the lines in the NG is about four times that in the PC. The intensity of the lines has been found to be proportional to p^α , where α is constant which varies between 0.2–0.5 and depends on the wavelength. The lines' intensity increases linearly by increasing the discharge current, i.e., $I_{pq} = cI$ (mA), c is a constant which is found to vary between 0.07 to 0.7 in PC and 1.2 to 3.8 in NG and depends on the wave length.

Also, the mean electron temperature has been estimated using the ratio of the lines' intensities technique, for the PC and NG regions, and has been found to decrease with pressure and that their values has found to depend on the wave lengths of the two chosen lines. A comparison between the estimated electron temperature obtained by single-probe, double-probe, and optical-emission-spectroscopy techniques has been shown. The result in the PC region is much more closer than that in the NG region. However, a good agreement between the three techniques can be observed, especially in the general trend of variation of temperature with pressure [17]. Values of T_e derived from optical-emission-spectroscopy technique has been

found to be about 30% higher than that obtained by electric-probes techniques in the NG region and that has been rendered to the non-Maxwellian energy distribution in that region.

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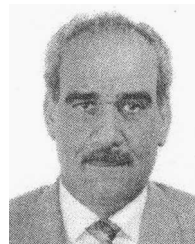
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