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Experimental Diagnostics and Characterization of Cold Atmospheric DBD Argon Plasma

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Abstract

Cold atmospheric dielectric barrier discharge (DBD) plasmas have gained significant attention due to their versatility in material processing, biomedical treatment, and agricultural enhancement. In this study, an argon-based atmospheric DBD system was developed by two horizontal circular metallic electrodes of diameter 5.0 cm at 3.0 mm air gap with a glass dielectric of thickness 1.5 mm by applying AC voltage of 4.7 kV and frequency 20.0 kHz. The plasma was characterized through integrated electrical and optical diagnostics to evaluate its discharge behavior and plasma parameters. In the power balance method, Lissajous plot and V–I approaches were used to estimate electron density, while the current density method provided additional validation. Using Optical emission spectroscopy (OES), the electron temperature (T_e) *was determined as 0.88 and 1.03 eV employing the line intensity ratio and Boltzmann plot methods, whereas density* (n_e) *was found as* 3.2×10^{23} and $2.6 \times 10^{16}\ m^{-3}$ *by Saha–Boltzmann equation and Stark broadening method respectively. In the electrical method,* n_e *was calculated as* $1.3 \times 10^{17}, 1.8 \times 10^{17}$, and $3.2 \times 10^{18}\ m^{-3}$ *using Lissajous plot, I–V, and current density methods respectively. The low electron temperature confirmed that the DBD plasma was a non-thermal. It is revealed that the Saha–Boltzmann method interprets more electrons than actually exist as it is based on LTE, while the Stark method measures the actual microfield effect of real electrons. The combined diagnostic approaches provide a reliable framework for deep understanding of cold atmospheric DBD plasmas for practical applications in low-temperature plasma processing.*

Keywords: non thermal plasma, AC voltage, characterization, electron density, electric field, and OES.

1. Introduction

Cold atmospheric dielectric barrier discharge (DBD) plasma has become extensive attention over the past two decades indicating to their wide applicability in material processing, surface activation, biomedical treatment, and sustainable agriculture [1,2]. This non-thermal plasma operated near room temperature produces a large number of reactive species, ions, electrons, exited articles, and ultraviolet radiations, making them ideal for temperature-sensitive applications. In DBD configurations, one or two dielectric materials separate the metallic electrodes, preventing arcing and ensuring a formation of micro-discharges during each AC voltage cycle [3, 4]. Understanding the fundamental plasma parameters like electron density (n_e) and electron temperature (T_e) is essential for optimizing discharge stability and chemical reactivity. Accurate characterizations of these quantities require complementary diagnostic techniques, as DBD plasma is highly transient and spatially inhomogeneous. Electrical and optical diagnostic approaches, therefore, act as indispensable tools to describe plasma behaviors under different operating conditions [5, 6].

Electrical characterization provides a direct deep understanding of the energy transfer between the power source and the plasma. The power balance method, employing either the Lissajous plot or the current–voltage (I–V) method, measures the energy consumed per discharge cycle and indirectly determines the electron density [7, 8]. The Lissajous Figure, plotted between charge and applied voltage, yields the discharge power from the enclosed area, allowing estimation of electron density when coupled with Bohm's criterion and energy loss parameters [9, 10]. Similarly, the I–V method interprets the instantaneous power from the product of measured applied voltage and plasma current, offering a simplified yet reliable estimation of plasma conductivity [11]. Complementing these, the current density method inter connects the measured discharge current, the electron drift velocity and mobility, providing an alternative estimation of electron density under homogeneous discharge conditions [4, 12]. These electrical approaches are essential for correlating input electrical power with plasma kinetics, thereby establishing the foundation for energy-resolved plasma diagnostics.

Optical emission spectroscopy (OES) offers a non-intrusive method to characterize the micro-physical properties of cold atmospheric DBD plasma with high temporal and spatial resolution. In particular, the line intensity ratio and Saha–Boltzmann relation are widely used to estimate electron temperature and electron density based on the relative intensities of spectral lines from different excitation or ionization stages [13]. The Saha–Boltzmann method is based on excitation and ionization equilibria under partial local thermodynamic equilibrium (PLTE), enabling simultaneous determination of n_e and T_e [14, 15]. For independent verification, the Stark broadening method investigates the full width at half maximum (FWHM) of spectral lines, typically argon or hydrogen transitions, to determine n_e based on the perturbation of energy levels by charged particles [16, 17]. Furthermore, the Boltzmann plot method depends a set of atomic emission lines to determine electron temperature by plotting the logarithm of normalized line intensity and excitation energy [18, 19]. Together, these optical techniques provide a comprehensive evaluation of plasma excitation, ionization, and emission that complement electrical diagnostics.

The variation of plasma parameters such as electron density and temperature with applied voltage, electrode gap, and dielectric thickness reveals the complex interplay between electric field distribution and gas kinetics. Increased applied voltage typically enhances electron acceleration and ionization rate, resulting in higher n_e, whereas larger air gaps or thicker dielectric barriers reduce discharge current and limit micro-discharge formation [20, 21]. Comparative studies have shown that the integration of electrical and optical diagnostics ensures cross-validation of derived parameters and improves measurement accuracy, particularly under atmospheric pressure where collisional processes dominate [5, 11].

The present work focused on generation and characterize ADBD plasma after which to calculate the plasma parameters. Therefore, a systematic diagnostic approach combining power balance, current density, line intensity ratio, Stark broadening, Saha–Boltzmann, and Boltzmann plot methods allows for precise determination of n_e and T_e and provides a deeper understanding of cold atmospheric DBD plasma dynamics. Further, the variation of electron density in the plasma with applied voltage, DBD thickness and air gap was analyzed.

2. Experimental Arrangement

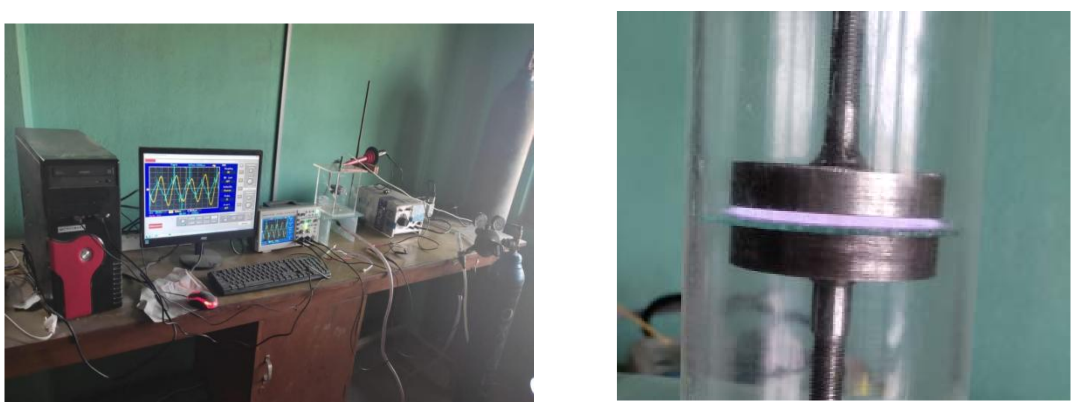


Figure 1. Photographs of production of DBD plasma.

The experimental setup for generating cold atmospheric dielectric barrier discharge (ADBD) argon plasma consisted of two identical circular metal electrodes (5.0 cm diameter) separated by a 3.0 mm air gap. A 1.5 mm thick glass plate served as the dielectric barrier on the grounded lower electrode, while the upper electrode was connected to a high-voltage AC source in the range of 0–30 kV and 0–100 kHz. Argon gas was supplied through a central inlet in the upper electrode at a controlled flow rate of 2.0 standard liter per minute (slpm). Electrical diagnostics were performed by recording current–voltage (I–V) waveforms using a Tektronix P6015A high-voltage probe, a Pearson Model 6585 current probe, and a Tektronix TDS2000 oscilloscope. Optical emission spectroscopy (OES) using an HR1 spectrometer (ASEQ Instruments) with a 10 µm slit and 300 gr/mm grating detected plasma emissions (200–830 nm) via a fiber optic cable placed 1.0 cm from the discharge region.

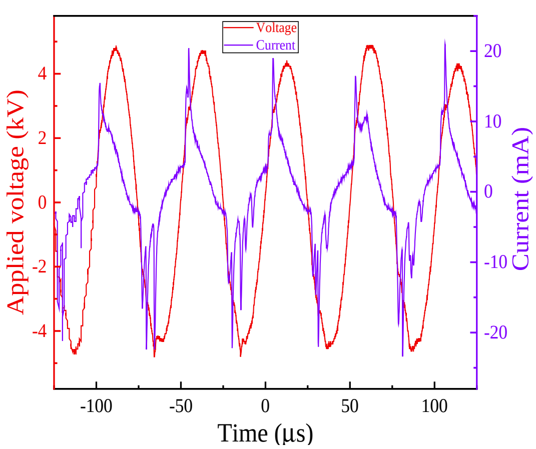
3. Results and Discussions

This section explains the electrical and optical characterizations of cold atmospheric DBD plasma to evaluate plasma parameters like electron density and electron temperature by different methods discussed below.

3.1. Electrical Characterization

The electrical characteristics of the cold atmospheric DBD plasma were analyzed to understand the discharge behavior and energy supply under different operating conditions. The wavefoms of applied voltage and discharge current were recorded using an digital oscilloscope to evaluate the discharge parameters. The electron density in the plasma was calculated using power balance and current density methods.

3.1.1. Power Balance Method



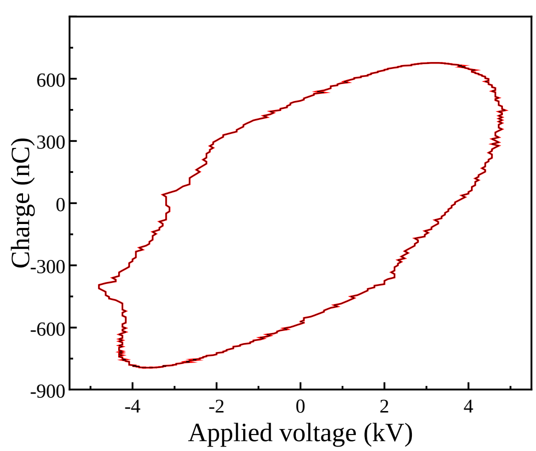


Figure 2. (a) V-I waveforms and **(b)** Lissajous plot at 1.5 mm DBD with 3.00 mm air gap at 4.7 kV of argon plasma.

The current–voltage (I–V) characteristics of the ADBD argon plasma recorded at 4.0 kV with a 3.00 mm air gap (Figure 2) display distinct current spikes aligned with the applied AC voltage waveform. These sharp peaks confirm the formation of numerous repetitive micro-discharges, a defining feature of dielectric barrier discharge (DBD) plasmas. Such behavior indicates that the discharge operates in a non-thermal regime where localized ionization occurs momentarily within each voltage cycle, consistent with reports on atmospheric-pressure argon and air plasmas [22].

The electron density (n_e) of the plasma was estimated using the power balance method, expressed as

$$n_e = \frac{P}{2Av_bE_{lost}} \quad \dots \dots \dots \dots \quad (1)$$

where $v_b = 2 \times 10^3$ ms^{-1}is Bohm velocity, $E_{lost} = 8 \times 10^{-18}$ J is energy lost by plasma and is balanced by the input power supply [23], $A = 19.6 \times 10^{-4}\, m^2$ is the area of each electrode. In this method, the power consumed (P) by the plasma is assumed to be equal to the input power supplied to the discharge, ensuring an energy balance essential for accurate plasma diagnostics.

3.1.2. Lissajous Method

The **Lissajous method** is a widely used electrical diagnostic technique to determine the **power dissipated** in a dielectric barrier discharge (DBD) plasma, which can then be used to estimate **electron density** through the **power balance method**. In this approach, the applied voltage across the DBD and the corresponding charge transferred (obtained from the voltage across a known capacitor connected in series) are plotted against each other to form a **Lissajous Figure**, typically a parallelogram or closed loop. The **area enclosed** by this plot represents the **energy dissipated per cycle** of the applied voltage [24].

The **average power (P)** consumed by the plasma is calculated from the area (A) of the Lissajous Figure using:

$$P = f \times E \quad \dots \dots \dots \dots \quad (2)$$

Where, energy (E)=area of Lissajious figure and f is the frequency of the applied AC voltage.

From the Lissajous Figure (3), E = 7.83×10^{-3} J. Using equation (1), power consumed in the plasma was found as 157.33 W at 20 kHz frequency. Hence, the electron density (n_e) was determined as $2.51\times10^{18}\,m^{-3}$ for argon at flow 2 lit/min with 3.0 mm air gap and 1.5 mm glass dielectric barrier for 4.7 kV applied voltage.

3.1.3. V-I Method

The Voltage–Current (V–I) method is an electrical diagnostic technique used to estimate the electron density in dielectric barrier discharge (DBD) plasma. In this approach, the applied voltage across the electrodes and the resulting discharge current are measured simultaneously [25]. The instantaneous energy consumed in the plasma was given by:

$$E=\int_0^T V(t)I(t)dt \quad \dots \dots \dots \dots \quad (3)$$

Where $V(t)$ and $I(t)$ are instantaneous voltage and current respectively.

In this method, energy lost was calculated using above integration of one complete cycle of AC and was found as 7.37×10^{-3} J which is multiply by frequency (f =20.0 kHz) of AC to get power dissipated as 147.37 W. Using equation (1), the electron density was determined as $2.35\times10^{18}\,m^{-3}$, which was very close to that calculated by Lissajous plot method.

3.1.4. Current Density Method

The **Voltage–Current (V–I) method** can also incorporate the concept of **electron mobility (μ_e)** to estimate the electron density (n_e) in a dielectric barrier discharge (DBD) plasma. In this approach, the plasma current (I) is measured along with the applied voltage (V), and average current was determined (I_{avr}). The average **current density** ($J_{avr}=I_{avr}/A$, where A is the area of microdischarges) is calculated. Using the electron drift relation [26]:

$$J_{avr}=n_e\mu_e eE \quad \dots \dots \dots \dots \quad (4)$$

where e is the electron charge, μ_e is the electron mobility in the gas, and E is the applied electric field, the electron density can be expressed as:

$$n_e=\frac{J_{avr}}{\mu_e eE} \quad \dots \dots \dots \dots \quad (5)$$

The electric field in the plasma was found as $E=\frac{V_p}{d}=\frac{4700}{0.003}=1.57\times10^{6}\,Vm^{-1}$. Using Bolsig+ software, the value of electron mobility (μ_e) was found to be 0.025 $m^2V^{-1}s^{-1}$considering collision between electrons. The average current was determined as 7.71×10^{-3} A and radius of a filament was takes as 100 μm. The total number of filaments was found using Origin Pro software at threshold height of 5% and was found to be 34 for a half cycle. The effective area of discharge was found to be 1.07×10^{-6} m^2, and the current density was calculated as 7.2×10^{3} A/m^2. Using equation (5), the electron density was found to be 1.18×10^{18} m^{-3}. Similarly using the rms value of current (20.9×10^{-3} A),the electron density was found to be 3.2×10^{18} m^{-3}.

3.2. Optical Characterization

Optical characterization of the plasma was carried out using Optical Emission Spectroscopy (OES) to analyze the emitted spectral lines. The emission spectra were used to determine key plasma parameters such as electron density and electron temperature. The Stark broadening method estimated electron density from the line width of Ar emission lines, while the Boltzmann plot and line intensity ratio methods evaluated electron temperature using selected spectral lines. These diagnostic methods provided insight into excitation mechanisms and plasma uniformity. Overall, optical diagnostics complemented electrical measurements for comprehensive plasma characterization.

3.2.1. Line Intensity Ratio Method to Determine Electron Temperature

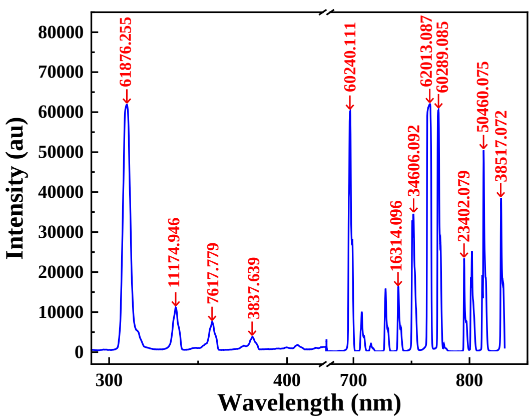


Figure 3: Optical emission spectra of ADBD argon plasma.

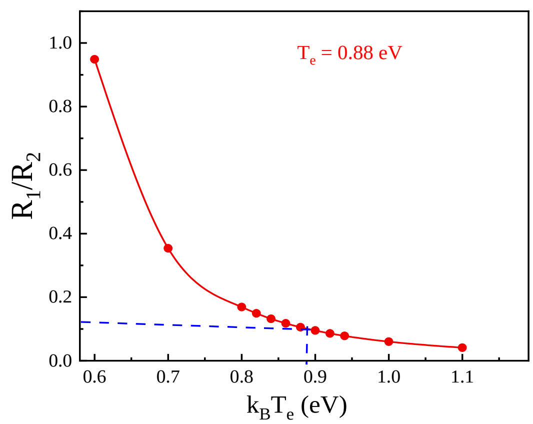


Figure 4. Variation of the ratio of R_1/R_2 with k_BTe.

Figure 3 shows the emission spectrum of ADBD argon plasma at 4.7 kV, revealing both atomic and molecular emissions. The most intense lines between 690–830 nm correspond to neutral argon (Ar I) transitions, while emissions in the 300–400 nm range are attributed to singly ionized argon (Ar II). The spectrum confirms that the plasma is primarily argon, with minor contributions from ambient atmospheric gases. Additionally, weak spectral bands associated with reactive nitrogen species (RNS) and hydroxyl (OH) radicals appear in the UV–visible region, demonstrating the plasma's capacity to produce chemically active species. These reactive species are important for processes such as seed surface modification and biochemical activation.

The electron temperature of the plasma (T_e) can be calculated by the line intensity ratio method [27], choosing two for Ar I (696.8 and 750.7 nm) and two for Ar II (309.8 and 380.8 nm) as:

$$\frac{R_1}{R_2}=\frac{I_1/I_2}{I_3/I_4}=\left(\frac{A_{pq}}{A_{xy}}\right)\left(\frac{g_p}{g_x}\right)\left(\frac{\lambda_{xy}}{\lambda_{pq}}\right)\left(\frac{A_{uv}}{A_{rs}}\right)\left(\frac{g_u}{g_r}\right)\left(\frac{\lambda_{rs}}{\lambda_{uv}}\right)\exp\left[-\frac{E_p-E_x-E_r+E_u}{k_B T_e}\right] \quad \dots\dots\dots(6)$$

Where R =intensities ratio of two spectral lines, I = intensity of the spectral line,

A_{ij} = probability of the transition i→j, g_i = statistical weight of the upper levels,

λ = wavelength of the transition line, E_i = energy of the upper level, k_B = Boltzmann constant.

The values of A_{ij}, g_i, and E_i for Ar I and Ar II lines taken from the NIST Atomic Spectra Database [28] are represented in **table 1** given below.

Table 1. Spectroscopic data of spectra of Ar I and Ar II to determine T_e.

Lines	Transition	Intensity (au)	A_{ij} (s^{-1})	Wavelength (nm)	g_i	E_i (eV)
Ar I	p→q	I_1=60240.111	$A_{pq}=6.4\times10^{6}$	$\lambda_{pq}=696.9$	$g_p=3$	$E_p=13.328$
Ar I	r→s	I_3= 34606.092	$A_{rs}=4.0\times10^{7}$	$\lambda_{pq}=751.6$	$g_r=1$	$E_r=13.273$
Ar II	x→y	I_2= 61876.255	$A_{xy}=4.4\times10^{8}$	$\lambda_{pq}=309.2$	$g_x=6$	$E_x=23.874$
Ar II	u→v	I_4= 3837.639	$A_{uv}=1.0\times10^{6}$	$\lambda_{pq}=380.6$	$g_u=6$	$E_u=19.680$

Using these values, equation (6) simplifies to

$$\frac{R_1}{R_2}=9.6\times10^{-4}\exp\left(\frac{4.14}{k_B T_e}\right) \quad \dots\dots\dots\dots \quad (7)$$

From experimental data, the intensity ratio R_1/R_2 was found to be 0.108. Using this value in conjunction with Figure 4, the electron temperature of the plasma was determined to be 0.88 eV. This result confirms that the dielectric barrier discharge (DBD) plasma operates in a non-thermal regime.

3.2.2. Saha-Boltzmann Relation to Determine Electron Density

The Saha–Boltzmann relation is a fundamental method used to estimate the electron density (n_e) in plasmas by combining ionization equilibrium (Saha equation) with excited-state population distribution (Boltzmann distribution). The Saha equation requires partial local thermal equilibrium (PLTE) and relates the ratio of ionized to neutral species in the plasma to the electron density and electron temperature, while the Boltzmann relation describes the population of atoms or ions in excited states based on their energy levels. By measuring the intensities of spectral lines corresponding to neutral and ionized species using optical emission spectroscopy (OES), one can determine the electron temperature and, consequently, the electron density [29].

By selecting one Ar I line and other Ar II line, the electron density in PLTE was calculated as:

$$n_e = 2\left(\frac{I_1}{I_2}\right)\left(\frac{\lambda_1}{\lambda_2}\right)\left(\frac{A_2}{A_1}\right)\left(\frac{g_2}{g_1}\right)\left(\frac{2\pi m_e k_B T_e}{h^2}\right)^{3/2} \exp\left(-\frac{E_1 - E_2 + E_i}{k_B T_e}\right) \quad \ldots \ldots \ldots \quad (7)$$

Where I_1, λ_1, λ_1, g_1 and E_1 are for neutral Argon (Ar I line), E_i=ionization energy of Argon (15.76 eV), and I_2, λ_2, λ_2, g_2 and E_2 are for ionized Argon (Ar II line). These values are represented in table 2 given below.

Table 2. Spectroscopic data of spectra of Ar I and Ar II to determine n_e.

Lines	Intensity (au)	A_{ij} (s^{-1})	Wavelength (nm)	g_i	E_i (eV)
Ar I	34606.09	40000000	751.6	1	13.27
Ar II	3837.64	1000000	380.6	6	19.68

Using these values of table 2 in equation (7), the value of electron density in the plasma was determined as 3.2×10^{23} m^{-3} for 4.7 kV with air gap 3.00 mm at 2 slpm argon flow using 1.5 mm thick glass dielectric barrier. This method assumes overestimation of ionization and, consequently, higher electron density was found than actually present.

3.2.3. Stark Broadening Method

The emission spectra of the plasma were also employed to determine the **electron density (n_e)** using the **Stark broadening method**. In this approach, the argon spectral line at 696.98 nm was selected. The **Stark broadening width ($\Delta\lambda_{Stark}$)** was obtained from the **full width at half maximum (FWHM)** of the spectral line, and its value was then used in Equation (8) to calculate the electron density under various plasma conditions [17]. In essence, the electron density can be calculated directly from the measured FWHM of the chosen spectral line using the relation:

$$\Delta\lambda_{Stark} = 2\times10^{-11}\, n_e^{2/3} \quad \ldots \ldots \ldots \ldots \quad (8)$$

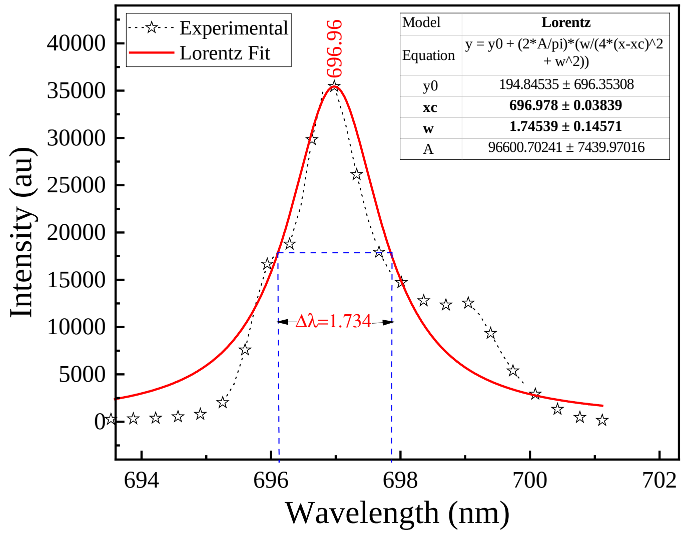


Figure 5. Stark broadening of spectral line at 696.98 nm wavelength of Ar I atom.

A selected spectral line of wavelength 696.98 nm was carried nonlinear fit by Lorentz as shown in Figure 5. From this Figure, the value of wavelength at FWHM was 1.75 nm. Using this value in equation (8), the electron density was found as 2.6×10^{16} m^{-3} for 4.7 kV with air gap 3.0 mm at 2 slpm argon flow using 1.5 mm thick glass dielectric barrier.

3.2.4. Boltzmann Plot Method

The Boltzmann plot method is a widely used optical diagnostic technique to estimate the electron temperature (T_e) in plasmas, particularly for low atmospheric pressure discharges like DBD [18] . This method depends on the relative intensities of several emission lines from the same atomic species.

According to the Boltzmann distribution, the population of atoms in an excited state is related to the electron temperature by

$$\text{In}\left(\frac{\lambda I}{hcA_{ij}g_i}\right) = \frac{E_i}{k_B T_e} + C \quad \dots \dots \dots \dots \quad (9)$$

Where, λ = wavelength of spectral line, E_i = excitation energy of upper level i,

g_i = statistical weight, A_{ij} =transition probability from i to j level, I = relative intensity, h= Planck's constant, c=velocity of light, T_e=electron temperature, k_B=Boltzmann constant, and C =some constant.

Table 3. Spectroscopic data of Ar I spectrum to determine T_e.

Intensity (au)	A_{ij} (s^{-1})	Wavelength (nm)	g_i	E_i (eV)
35447.268	6.40×10^6	696.54	3	13.3279
15041.221	4.50×10^7	750.39	1	13.4799
58319.211	2.45×10^7	763.51	5	13.1718
3766.258	2.00×10^6	706.87	3	14.8483

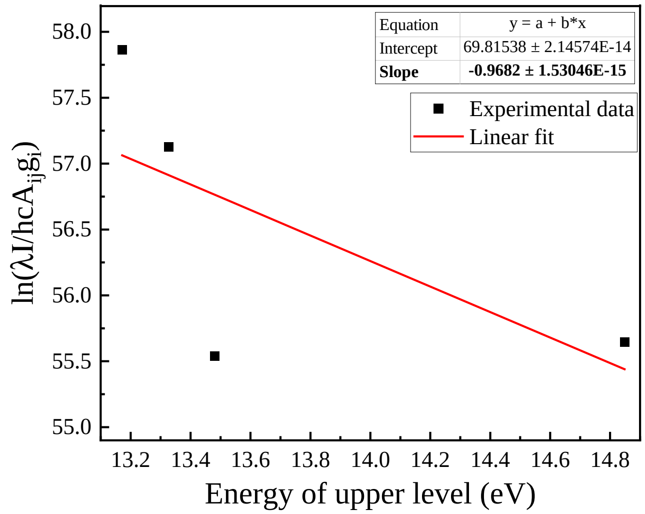


Figure 6. Boltzmann Plot to determine electron temperature.

In this method, several suitable lines of Ar I were chosen from the optical spectra of argon discharge and corresponding required optical parameters are represented in table 3 as given below. The values of $\ln\left(\frac{\lambda I}{hcA_{ij}g_i}\right)$ were determined and the graph between $\ln\left(\frac{\lambda I}{hcA_{ij}g_i}\right)$ and E_i is a straight line as shown in the Figure 6. Its slope was found as -0.968 $(eV)^{-1}$ whose reciprocal gives of $-k_B T_e$. Hence, the value of T_e was determined as 1.03 eV.

4. Conclusions

Extensive electrical and optical diagnostics were successfully employed to explore the behavior of cold atmospheric dielectric barrier discharge (DBD) argon plasma. The electrical characterization was carried out to determine electron density, where as both the electron density and temperature were calculated using optical characterization. Electron temperatures obtained from line intensity ratio and Boltzmann plot methods confirmed the non-thermal nature of the DBD plasma. The Saha–Boltzmann approach yielded comparatively higher electron density due to its partial local thermodynamic equilibrium (PLTE) assumption, whereas the Stark broadening method provided a more accurate assessment under non-equilibrium conditions. The close agreement among different diagnostic methods validated the reliability of the integrated experimental approach. Overall, this study sets up a robust framework for precise characterization of the plasma, supporting the optimization of cold DBD plasmas for environmental, biomedical, and agricultural technologies.

5. Acknolegements

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6. References

1. Fridman, A. (2008). *Plasma chemistry*. Cambridge University Press.
2. Brandenburg, R. (2017). Dielectric barrier discharges: Progress on plasma sources and on the understanding of regimes and single filaments. *Plasma Sources Science and Technology, 26(5),* 053001.
3. Kogelschatz, U. (2003). Advances in dielectric barrier discharges. *Plasma Science, IEEE Transactions on*, *30(4)*, 1400–1408.
4. Raizer, Y. P., Allen, J. E., & Kisin, V. I. (1991). Gas Discharge Physics (Springer, Berlin).
5. Kumar, N., et al. (2021). Electrical and optical diagnostics of atmospheric pressure plasma jet for biomedical applications. *Plasma Research Express*, *3(4)*, 045009.
6. Sarani, A., Nikiforov, A., & Leys, C. (2010). Atmospheric pressure plasma jet in Ar and Ar/H_2O mixtures: Optical emission spectroscopy and temperature measurements. *Physics of Plasmas*, *17(6)*, 063504.
7. Massines, F., et al. (1998). Experimental characterization of the atmospheric pressure glow discharge in helium and comparison with modelling results. *Plasma Sources Science and Technology*, *7(3),* 310–319.
8. Kogelschatz, U. (2002). Dielectric-barrier discharges: Their history, discharge physics, and industrial applications. *Plasma Chemistry and Plasma Processing*, *23(1),* 1–46.
9. Yuan, C., et al. (2020). Power dissipation and electron density analysis of DBD plasma using Lissajous Figure method. *Plasma Science and Technology*, *22(12)*, 125403.
10. Shi, J., et al. (2019). Electrical and optical diagnostics of nanosecond pulsed DBD plasma in air. *Plasma Processes and Polymers*, *16(3)*, 1800169.
11. Sretenović, G. B., et al. (2011). Electrical and optical characterization of DBD plasma in air and argon. *Plasma Sources Science and Technology*, *20(1)*, 015015.
12. Luque, A., & Ebert, U. (2014). Growing discharge trees with self-consistent charge transport: The collective dynamics of streamers. *New Journal of Physics*, *16(1),* 013039.
13. Aguilera, J. A., & Aragón, C. (2007). Multi-element Saha–Boltzmann and Boltzmann plots in laser-induced plasmas. Spectrochimica Acta Part B: *Atomic Spectroscopy*, *62(3),* 319–329.
14. Konjević, N., & Roberts, J. R. (1976). Plasma broadening of spectral lines from singly and doubly ionized atoms. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 16(5), 497–523.
15. Moussounda, P., et al. (2021). Evaluation of local thermodynamic equilibrium in argon DBD plasma using Saha–Boltzmann method. *Journal of Applied Physics*, *129(10)*, 103301.

16. Nikiforov, A. Y., Leys, C., González, M. A., & Walsh, J. L. (2015). Electron density measurement in atmospheric pressure plasma jets: Stark broadening of hydrogenated and non-hydrogenated lines. *Plasma Sources Science and Technology*, *24(3)*, 034001.
17. Dong, L., Ran, J., & Mao, Z. (2005). Direct measurement of electron density in microdischarge at atmospheric pressure by Stark broadening. *Applied Physics Letters*, *86(16)*, 161501.
18. Balcon, N., Aanesland, A., & Boswell, R. (2007). Pulsed RF discharges, glow and filamentary mode at atmospheric pressure in argon. *Plasma Sources Science and Technology*, *16(2)*, 217–226.
19. Nersisyan, G., et al. (2022). Time-resolved optical emission study of DBD plasma in Ar and Ar/O_2 mixtures. *Physics of Plasmas*, *29(6)*, 063507.
20. Tay, W. J., et al. (2022). Impact of dielectric barrier thickness on discharge characteristics of atmospheric DBD plasma. *Journal of Physics D: Applied Physics*, *55(12)*, 125202.
21. Wang, C., et al. (2021). Effects of air gap and voltage on DBD plasma uniformity at atmospheric pressure. *IEEE Transactions on Plasma Science*, *49(5)*, 1658–1666.
22. Tyata, R. B., & Subedi, D. (2014). Measurement of electron density in dielectric barrier discharge using power balance method. *Journal of Scientific and Engineering Research*, *2(4)*.
23. Topper J., Lindmayer M . and Juttner B., 2000. XIII international Conf. on Gas Discharge and their Application, (Glasgow, Scotland, 03: 08 Setember 2000).
24. Shah, A. K., Shrestha, R., Sah, R. L., Nakarmi, J. J., & Mishra, L. N. (2022). Experimental study of dielectric barrier discharge in an atmospheric air pressure and its electrical characterization. JP Journal of Heat and Mass Transfer, 30, 135-150.
25. Yambe, K., Izumida, T., & Akatsuka, H. (2022). Estimation of electron density and temperature by continuum spectrum in a moving atmospheric-pressure nonthermal-equilibrium argon plasma
bullet. *IEEE Transactions on Plasma Science*, *50(10)*, 3593-3601.
26. Raizer, Y. P. (1991). Gas discharge physics. Berlin: Springer-Verlag. 449 p.
27. Sarani, A., Nikiforov, A. Y., & Leys, C. (2010). Atmospheric pressure plasma jet in Ar and Ar/H2O mixtures: Optical emission spectroscopy and temperature measurements. *Physics of Plasmas*, *17(6)*.
28. Kramida, A., Ralchenko, Y., & Reader, J. (2018). NIST atomic spectra database. *NIST standard reference database*, *78.*
29. Griem, H. R. (1997). *Principles of Plasma Spectroscopy*. Cambridge University Press.