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Effects of Variable Applied Voltage on Dielectric Barrier Discharge Plasma Parameters: Comparative Study

The purpose of the COMSOL Multiphysics program is to create a simulation that is similar to an experimental device. In this paper, a one-dimensional simulation for discus plate DBD is done in COMSOL Multiphysics software. DBD system, which used argon as the working gas and an ac power supply running at a frequency of 9.1 kHz, is reported in this study. Investigating the effects of voltage on temperature and electron density in our device, it is shown that an increase in voltage from 2 to 12 kV results in an increase in electron density from 5.405×10^{17} to 7.432×10^{17} cm^{-3} and also increasing the electron temperature. By utilizing COMSOL, results showed an excellent agreement between experiment and COMSOL simulations results. According to the study, electron density could reach orders of 1017 cm-3 by optimizing which control of applying Voltage. The results of this study provide important insights into the field of plasma technology and its applications, where they may serve as a basis for future extensive research.

Keywords: Plasma; Electron density; Electron temperature; DBD; COMSOL
Received: 04 November; **Revised:** 05 December; **Accepted:** 12 December 2023

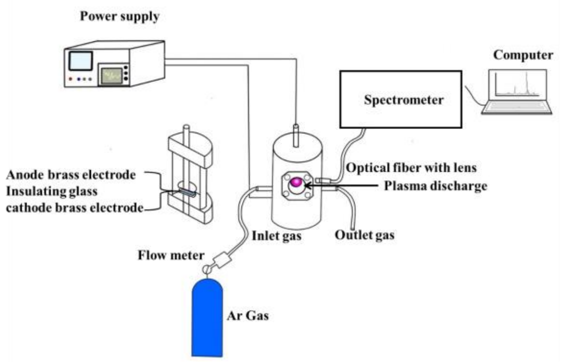
1. Introduction

Many research studies have explored non-thermal plasma, like dielectric barrier discharge plasma (DBD), for various applications due to its significant potential in technology. Non-thermal plasma, which can produce high-density plasma at room temperature, is widely favored for its eco-friendliness, cost-effectiveness, and independence from expensive specialized labs [1,2]. A dielectric barrier discharge, often known as a silent discharge or barrier discharge, involves using at least one electrode covered with a dielectric material. The dielectric layer serves as a safety measure, limiting electric current and preventing the occurrence of sparks or arc discharges [3]. Common materials used for this purpose are glass, ceramics, quartz, enamels, and epoxy. Among others [4,5], a dielectric barrier discharges (DBDs) exhibit a unique behavior, combining non-equilibrium and near-continuous properties. They are known for having high-energy electrons while keeping other heavy particles (neutrals and ions) at lower temperatures. DBDs generate various chemically active components, including electrons, free radicals, and ions, without significantly heating the surrounding gas. Because of these characteristics, DBDs find extensive use in applications such as gas purification (removing sulfur oxides, nitrogen oxides,, and volatile organic compounds), notably in the generation of ozone, the alteration of polymer surfaces, plasma-based vapor deposition, and pollution control, sterilization in medical applications water treatment, agriculture and numerous other technologies [6,7] micro discharge plasma parameters, especially electron density and temperature that affect the properties of plasma, additionally other number of factors, including flow rate, gas composition, applied voltage, frequency, electrode design, and dielectric type [1,8]. There must be coherence between theory and experiment in science. This implies that there is essentially a theoretical foundation for what is done empirically. We use the simulation technique to avoid the high cost on setup design and to prevent wasting time with the goal of applying the optimal conditions to real-world trials, and forecast plasma behavior under various circumstances especially if the input data that the program requires are accurate. It will give us results that are very close to the experimental results [9]. In this study, we use the COMSOL Multiphysics program to simulate the phenomenon and investigate the degree to which experimental data match the simulation [10].

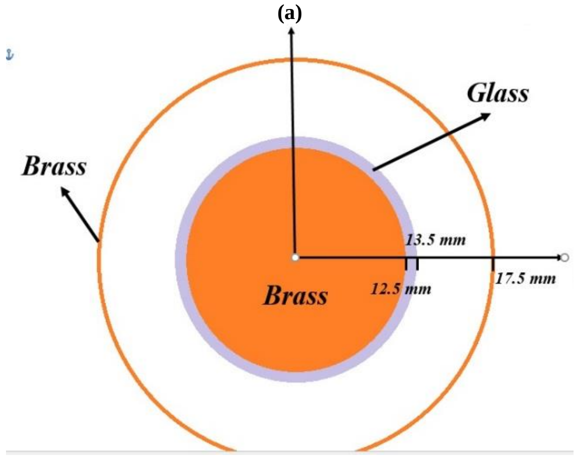
There are two goals of this work, the first goal is to thoroughly examine how the dielectric barrier discharge (DBD) plasma behaves when the voltage in the system is changed, and the second is to investigate if the simulation of the experiment using COMSOL program gives a good match with the experimental work result. Electron temperature, electron density, plasma frequency, and Debye length – all of which are impacted by voltage variations – were measured using spectroscopy techniques, and the outcomes of the simulation and the experiment were compared.

2. Experimental Part and Plasma diagnostics

The plasma generation chamber is made up of two solid brass cylinders, each measuring 40 mm in height and 25 mm in diameter. They are positioned about 5 mm apart. A thin layer of insulating glass, just 1 mm thick, is sandwiched between these two cylinders. The chamber itself is cylindrical and constructed from Teflon material. It has a 50 mm diameter and includes two openings: one for introducing argon gas and the other for letting it escape. To ignite the plasma, we use an alternating electric current source that can vary in frequency. This source provides a high voltage in the range of 0 to 20 kilovolts, as well as the argon gas flow rate was kept constant at 2 L/min. In this setup, the electric field created by the voltage difference between the electrodes is uniform. This ensures that the resulting plasma occupies the entire space from just beneath the anode to the surface of the dielectric covering the lower electrode (cathode) [11]. As depicted in Fig. (1), the AC dielectric barrier discharge (DBD) system that was used in this work, (a) for experimental setup, and (b) simulation setup in the COMSOL software.



(a)



(b)

Fig. (1) (a) The experimental setup design for the Dielectric Barrier Discharge, and (b) Schematic design of the simulation setup

A discharge begins when the breakdown voltage is attained. Ionization takes place during discharges in gases at atmospheric pressure, and a large number of random arcs emerge in the operating gap between the two electrodes. [12]. The layer is charged by the accumulation of the charge incoming ions or electrons, where they discharge in microseconds, reforming elsewhere on the surface. Moreover, the surface charge restricts the amount of charge that can be transported to the electrodes by lowering the electric field in order to prevent the glow discharge from turning into an arc [13]. This charge accumulation process is transient; as long as a sinusoidal voltage is applied, the process will repeat itself and reverse in the other way when the electric field potential is reversed. This so-called dielectric barrier is what causes the plasma to self-pulse, which in turn causes a nonthermal plasma to form at room pressure. [14]. The large electrodes and short spacing between them result in a large surface-to-volume ratio for the DBD. In addition to maintaining a low gas temperature, this encourages heat diffusion losses. [15]. Optical emission spectroscopy (OES) is one technique for diagnosing plasma. In fact, it's possible to say that the emission lines serve as the excited species' fingerprints, to determine the plasma's parameters such as plasma frequency, electron density, and Debye length. The plasma electron temperature was counted using Boltzmann plot method [16]

$$ln\left[\frac{\lambda_{ji}\,I_{ji}}{hcA_{ji}g_j}\right] = -\frac{1}{k_BT}\left(E_j\right) + ln\left|\frac{N}{U(T)}\right| \qquad (1)$$

where g_i is statistical weight, while I_{ji} is the relative emission line density between energy levels i and j, λ_{ij} is the wavelength (in nm), k_B is the Boltzmann constant, A_{ji} is the potential for radiation to be automatically transmitted from level i to the lower level j, E_j is the excitation energy for level i, N refers to the densities of the population of the state, $U(T)$ is the partition function, h is the Planck's constant, and c is the speed of light. Debye's length (λ_D) is calculated using the formula shown below [17]

$$\lambda_D = \left(\frac{\varepsilon_0\, k_B\, T_e}{n_e e^2}\right)^{1/2} \qquad (2)$$

where n_e is the density of the electrons, Free space permittivity is denoted by ε_0, e is the electron charge, and T_e is the electron temperature. Plasma frequency (ω_p) can be given as [18,19]:

$$\omega_p = \left(\frac{n_e\, e^2}{\varepsilon_0 m_e}\right)^{1/2} \qquad (3)$$

where m_e is the mass of the electron, and the rest of the parameters are known above

2.1 Governing Equations to DBD simulations

We use COMSOL Multiphysics program (version 6.1) to simulate the phenomenon. COMSOL software calculates the average electron density and electron energy that solved by COMSOL are respectively [20,21]:

$$\frac{\partial y}{\partial t}(n_e) + \nabla\cdot[-n_e(\mu_e\cdot E) - D_e\cdot\nabla n_e] = R_e \qquad (4a)$$

$$\frac{\partial y}{\partial t}(n_\varepsilon) + \nabla\cdot[-n_\varepsilon(\mu_e\cdot E) - D_\varepsilon\cdot\nabla n_\varepsilon] + E\cdot\Gamma_e = R_e \qquad (4b)$$

where n_e is the electron density, D_e is the electron diffusion coefficient, and Γ_e is the electron flux, R_e the rate of electron production, μ_e the electron mobility, n_ε is the electron energy density and E is the electric field

3. Results and Discussion

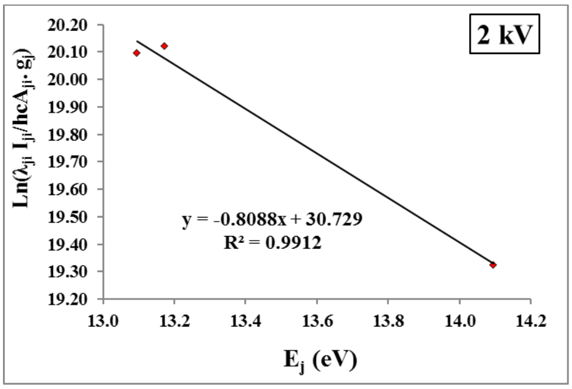
3.1 Optical Emission Spectroscopy (OES)

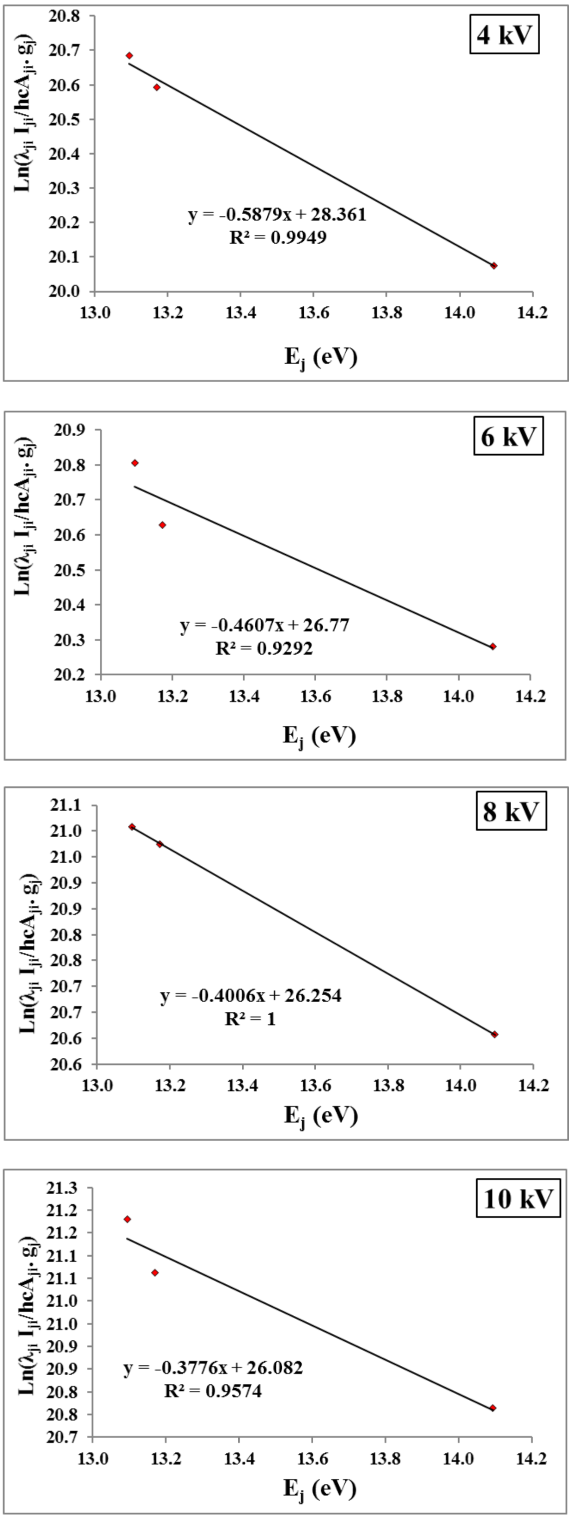
In order to investigate the effect of voltages applied on the spectra generated, figure (2) displays the emissions spectra of the generated plasma using various voltage values. According to NIST data [22], this figure exhibits a variety of peaks, the majority of which are associated with ArI. The results for the locations of the most important peaks in the spectrum at 696.54, 763.51, 772.38, 801.47, 811.53, 826.45, 842.46, and 912.30 nm, as well as found that the maximum intensity was at 763.6 nm at 12 kV.

According to the figure, as the applied voltage is raised, the peak intensity rises. Due to an increase in the potential difference between the electrodes, which gives the electrons sufficient excitation energy, the acceleration of the electrons increases with the potential difference. This causes more ionization collisions, which in turn increases the intensity of the plasma emission. This result which agrees with [16,23].

The relation between between ($Ln[\varepsilon_{ji}\lambda_{ij}/A_{ji}g_j]$) versus upper energy level (Ej) for the dielectric barrier discharge (DBD) system for each voltage was utilized to compute the T_e values using Eq. (1). The results are displayed in Fig. (3). Additionally, the fitting equation for each voltage as well as the statistical coefficient (R^2) are included in this figure.

The figure's results show that the range of 0.9292-1 eV is where the fluctuation in the (0,1) values occurs proving the accuracy of the linear fit. Electron density ne can be calculated by Eq. (2) of a different voltage the outcomes are shown in Fig. (4). We notice an increase in the electron density in the range of 5.405-7.432x10^{17} cm^{-3} with different applied voltages, while the electron temperature (T_e) in the range of 1.236-2.551. This value clearly resulted that density and temperature of electron depends on the applied voltage and we notice of the figure that the electron temperature increasing from 1.236 to 2.648 eV, with increasing applied voltage from 2 to 10 kV, respectively, while decreasing slightly to 2.551 eV with 12 kV. Table (1) displays the plasma properties. Such as plasma frequency, electron density, electron temperature, and Debye length. For DBD plasma, at various voltages of an atmospheric pressure.





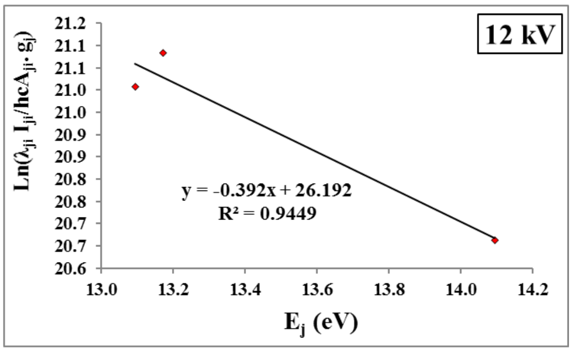


Fig. (3) Boltzmann plot for ArI peaks using the DBD system at various voltages

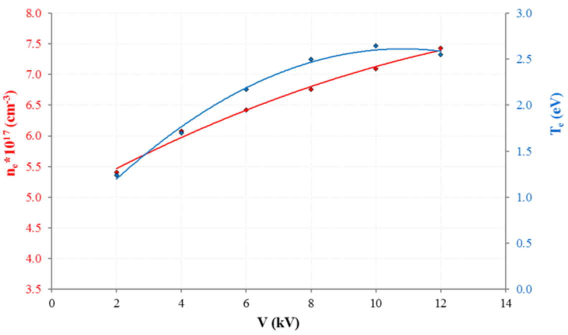


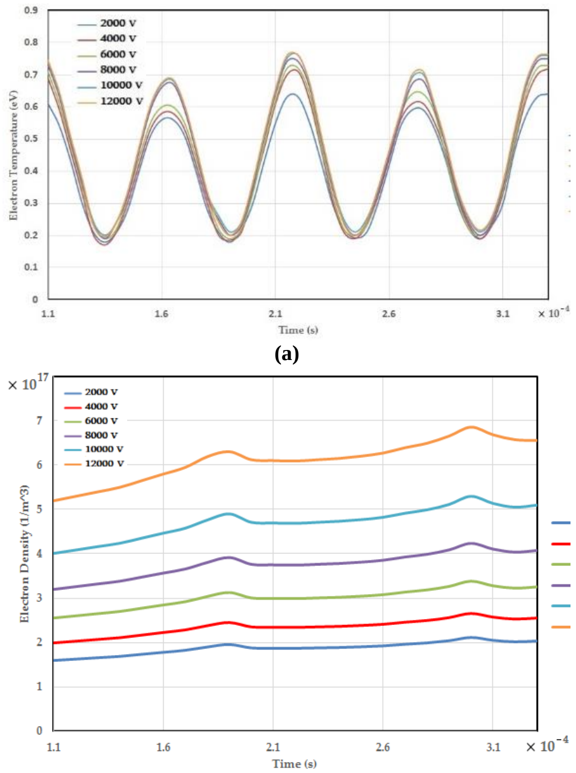
Fig. (4) The relationship between electron temperature (Te), electron density (ne) with Ar gas flow rates

According to that Figure and data listed in table (1), as the applied voltage between the two electrodes, is raised, electric field intensity in the electrodes gap increases, this is due to the fact that when the electrons are exposed to a high potential difference, they accelerate more and their kinetic energy increases, and thus their electron temperature increases. Although increasing the kinetic energy of the electrons causes an increase to more ionization collisions and thus an increase in the speed of the electrons.

The energy that the electrons gain as a result of acceleration is much greater than the energy that they lose as a result of the collisions. Therefore, we note that increasing the potential difference between the two electrodes causes an increase in the temperature of the electrons. However, this process is not achieved in absolute terms. Increasing the applied voltage also results in an increase in the density of particles, leading to heightened collisions. This, in turn, causes a reduction in the kinetic energy of the electrons and a subsequent decrease in electron temperature. Thus, it can be said that two factors are at play, competing for predominance whichever is predominant becomes the prevailing. And this maybe to explains the vacillated between the increase and decrease of electron temperature in different applied voltage. On the other hand, the electron density increases and thus an increase in the plasma emission intensity [24]. This result agrees with [23,25].

3.2 Simulation results

The simulation was carried out under constant conditions such as frequency of 9.1 Hz, a gas flow rate of 2 L/min, and fixed dimensions of setup, while voltage parameters that were changed in the range of 2 to 12 kV. Consequently, calculations were made for the electron temperature and electron density, and the results were compared with experimental data. A close examination of the COMSOL-provided diagrams for Fig. (5a) illustrate the electron temperature as a function of applied voltage; each point in the figure corresponds to a new run in the COSMOL with the specified working conditions.



(a)

(b)

Fig. (5) Simulation results from COMSOL of (a) electron temperature, and (b) electron density, of versus applied potential at atmospheric air pressure

Table (1) Plasma parameters at various voltages

V (kV)	T_e (eV)	FWHM (nm)	n_e x10^{17} (cm^{-3})	f_p x10^{12} (Hz)	λ_D x10^{-6} (cm)
2	1.236	0.800	5.405	6.602	1.124
4	1.701	0.900	6.081	7.003	1.243
6	2.171	0.950	6.419	7.195	1.366
8	2.496	1.000	6.757	7.382	1.428
10	2.648	1.050	7.095	7.564	1.436
12	2.551	1.100	7.432	7.742	1.377

We notice the electron temperature curves increase against applied voltage increases. In Fig. (5b), we see the electron density at the mentioned voltages, also increased when the potential difference between the two electrodes increased. Based on the data obtained in this simulation, and according to Fig. (5a,b), we find that there is a good match with experimental data for the electron temperature and electron density. Taking into account the small difference in the accuracy of the values between simulation and practical values.

4. Conclusion

In this work, the effects of applied voltage on DBD plasma characteristics are investigated experimentally and compared with the outcomes of a COMSOL Multiphysics simulation. The study examined how different voltages affected the parameters for plasma electron temperature and density. It has been demonstrated that the simulation results are consistent with the experimental data, suggesting that this approach is a successful substitute for practical experiments, the results showed that the behavior of the electron temperature and density changed with applied voltage, indicating that increasing the voltage caused the electron density to increase. Still, the temperature of the electrons increases.

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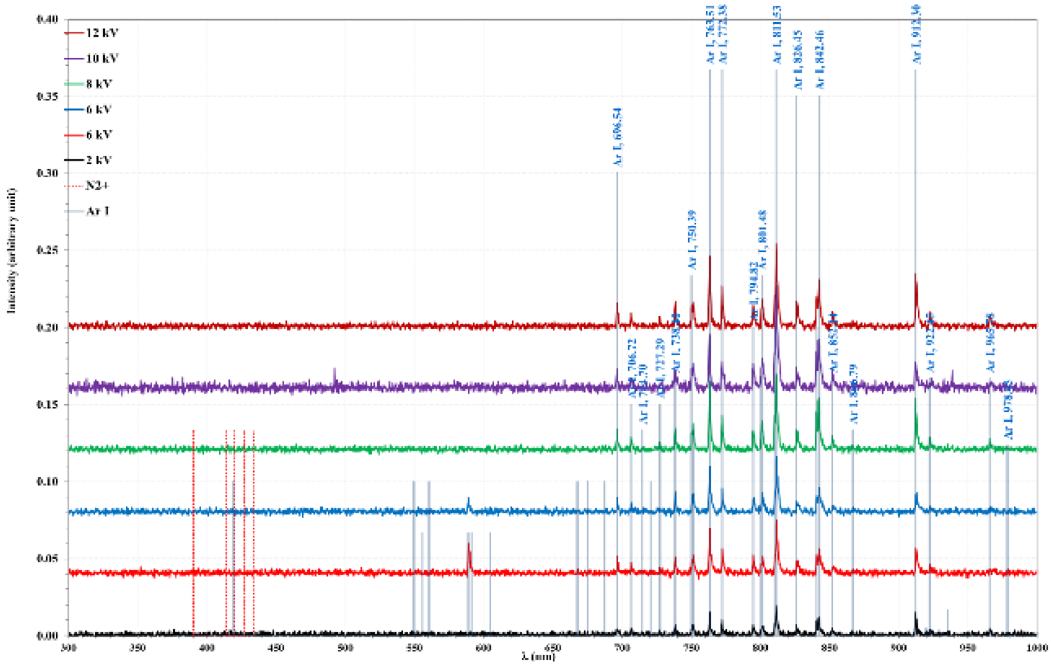

Fig. (2) The optical emission spectra of DBD plasma produced at various voltages of 2, 4, 6, 8, 10, and 12 kV