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Influence of Electrode Shape on Dielectric Barrier Discharge Plasma Characteristics

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Abstract:

Dielectric barrier discharges (DBDs) are a typical example of non-thermal atmospheric-pressure gas discharges generated in configurations with an insulating (dielectric) material between the electrodes. This work is to provide a better understanding of the breakdown processes and plasma formation, as well as the effect of the shape and configuration of electrodes on the produced plasma parameters, since the choice of electrode materials, geometry, and arrangement can influence plasma parameters such as electron density, electron energy distribution, and plasma temperature; understanding these characteristics helps optimize the plasma for specific applications. Three types of DBD plasma systems were presented in this work by varying the electrode shape and arrangement; the results indicated that electrode shape and configuration play essential roles in determining plasma parameters.

Keywords: DBD Plasma, Non-thermal plasma, Atmospheric Pressure Glow Discharge (APGD), Electrode geometry, OES, Plasma parameters, Boltzmann plot method.

Introduction:

Non-thermal plasmas, a partially ionized gas, are characterized by having a significant population of energetic electrons that are not in thermal equilibrium with the natural gas. These plasmas are mostly generated at low pressures by applying electric fields or discharges to a gas (air, argon, etc.) (Miao et al., 2023; Hayif, Hadi and Hashim, 2024). In non-thermal plasmas, the electron energy distribution does not obey a Maxwell-Boltzmann distribution (non-Maxwellian). The electron population can have a high-energy tail, with a small fraction of electrons possessing much higher energies than expected in thermal equilibrium; this means that the electron temperature is significantly higher than the neutral gas temperature. This departure from thermal equilibrium is due to electric fields, collisions, and other non-equilibrium effects (Harvey *et al.*, 2023).

Non-thermal plasmas are typically generated by applying an electric field or supplying energy to a gas. This can be achieved through various methods, including electrical discharges, microwaves, lasers, or photoionization. The energy input causes the gas to become partially ionized, creating a mixture of free electrons, ions, and neutral particles (Hassan and Hashim, 2024).

The electrical discharge between any two electrodes separated by a dielectric barrier is known as dielectric barrier discharge (DBD); the dielectric barrier serves to limit the current flow and prevent spark-to-arc transition in the generated non-thermal plasma (Kadhim, Abbas and Abdulameer, 2022); this technique is a safe and low-cost method to produce plasma in the atmospheric without a vacuum or other preparation conditions (Shao *et al.*, 2010). Glass is a typical dielectric barrier material; however, other materials, such as quartz, ceramics, plastic, mica, and silicon rubber can be employed (Kadhim, Abbas and Abdulameer, 2022).

DBD plasma is effectively employed in many applications due to its unique properties, such as material surface modification (D’Agostino *et*

al., 2009), pollution control (Hijosa-Valsero, Molina and Bayona, 2014), ozone generation, and sterilization processes (Zhang *et al*., 2012).
DBD is considered a flexible working medium in terms of the geometrical configuration of electrodes and the dielectric barrier material, as well as other operational parameters, and operates in an atmospheric-pressure environment. This means it can be well adapted to specific applications (Muryoush, 2022).
DBD plasma can be generated at low atmospheric pressure; however, the discharge has a short lifetime due to charge-carrier accumulation at the dielectric surface, which produces an opposing field to the externally applied voltage, causing the discharge to disappear. The heavy ions and neutral atoms absorb far less energy from the alternating field; therefore, the DBD plasma is a non-thermal plasma in which the electrons are of high temperature, but the neutral gas and the ions are near room temperature, which also is suitable for medical applications or any application sensitive to high temperatures (Yang *et al*., 2013).
Optical emission spectroscopy (OES) is commonly used for plasma investigation because it can analyse the plasma's elemental composition, electron temperature, and electron density. OES provides valuable insights into the physical and chemical processes occurring within the plasma, helping to understand its properties and behaviour.
The Boltzmann plot method is a simple, widely used spectroscopic measurement technique, especially for determining plasma parameters (Ohno *et al*., 2006; Aadim *et al*., 2020).
Electrodes geometry in a DBD plasma system plays an important role in the properties of the generated plasma, where the electrode shape influences the distribution of the electric field within the DBD device; different electrode shapes can result in variations in the electric field strength and distribution across the gap. This, in turn, affects the plasma's breakdown voltage, discharge current, and power consumption, influencing the ionization and excitation processes occurring in the plasma. On the other hand, the shape of the electrodes may lead to localized variations in plasma properties. Furthermore, the electrode

geometry may affect gas flow or distribution within the DBD plasma system. Different electrode configurations can alter gas flow patterns and the transport of charged particles produced in the plasma region. Also, the system's electrode form and structure can influence the electron density and temperature of the generated plasma. These variances may affect applications that require plasma under special conditions, such as surface treatment.

In the atmospheric pressure range, optical techniques based on spectral line emission intensity are frequently employed to assess internal plasma parameters such as electron temperature (T_e) and electron density (n_e). The electron temperature in the plasma is calculated using the Boltzmann plot technique. It is a simple, frequently used method for optical emission spectroscopy (OES). The relative intensities measured by OES for two lines of the same element. To realistically apply the Boltzmann plot approach, the excitation level must be obtained in a partial local thermal equilibrium (p-LTE) state (Ohno *et al.*, 2006). Based on OES spectrum analysis T_e may be calculated using the Boltzmann relationship expression (Okubo *et al.*, 2001; Hashim, Hadi and Hayif, 2024):

$$\ln\left(\frac{\lambda_{ji} I_{ji}}{hcA_{ji}g_{ji}}\right) = \frac{-1}{kT_e}(E_j) + \ln\left(\frac{N}{U(T)}\right) \quad (1)$$

where λ_{ji} represents the wavelength, I_{ji} represents the relative intensity of the emission line between i and j energy levels, k is Boltzmann's constant, A_{ji} represents the transition probability for spontaneous radiative emission from upper level (i) to the lower level (j), g_i represents the statistical weight of emitting upper level (i) of the studied transition, N represent the number density of the excited state , E_j represent the excitation energy of level (i).

The electron number density is an essential metric since it characterizes the plasma environment and achieves its equilibrium condition, which is normally evaluated by the Stark broadening. It may be calculated using

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the line width as follows (Hashim, Oudah and Hussein, 2023; Hayif, Hashim and Hadi, 2025):

$$n_e = \left(\frac{\Delta\lambda}{2\omega_s\,(\lambda T_e)}\right) N_r \qquad (2)$$

where Δλ denotes the Line Full Width at Half Maximum (FWHM), ω_s is a parameter of Stark broadening (the value is found in standard tables), N_r is reference electron density that is equal to $10^{16}cm^{-3}$ for neutral atoms while for single charged ions, it is $10^{17}cm^{-3}$.

Plasma frequency of electron f_p can be computed (Kizling and Järås, 1996; Hayif, Hadi and Hashim, 2025b):

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

where f_p represents the frequency of plasma electron, ε_o is the free space permittivity, n_e represents the plasma electron density, e and m_e are charge and mass of electron respectively.

Another crucial parameter is Debye length, or shielding, which determines the plasma's quasi-neutrality, where charged particles in plasma interact with one another to lessen the influence of the produced electric field.

The Debye length may be calculated as (Kizling and Järås, 1996) (Hayif, Hadi and Hashim, 2025a):

$$\lambda_D = \left(\frac{k\,T_e\,\varepsilon_o}{n_e\,e^2}\right)^{1/2} \qquad (4)$$

Experimental

The DBD system used in this work consists of two copper cylindrical electrodes, each 5 cm in diameter and 2 cm thick, surrounded by Teflon to isolate them. One of these electrodes was a plane disc, while the other had a square zigzag disc pattern, as shown in Figure 1; the space between the two electrodes is 5 mm. The dielectric barrier (a 2 mm-thick glass slide) is placed between the electrodes. Under atmospheric air pressure,

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an AC voltage of 18 kV was applied between the two electrodes to generate volume plasma on the dielectric barrier. The effects of electrode shape and arrangement were studied by varying both. Three patterns of arranging the electrodes were used, as shown in Figure 2; in the first, both electrodes are plane discs, as shown in Fig. 2a; in the second, one of the electrodes is a plane disc, and the second is a zigzag disc so that the ground electrode is the plane surface, as shown in Fig. 2b. The third was that the ground electrode was the zigzag disc, as shown in Fig. 2c.

The optical emission spectrometer was used to analyse the emission intensity of discharge zones in the current system to ascertain plasma properties by diagnosing the spatially integrated plasma light emissions over a wavelength range of 300 - 400 nm. NIST was used to identify emission lines (wavelengths/transition probabilities); the parameters T_e, n_e were computed using physical models (Boltzmann/Stark).

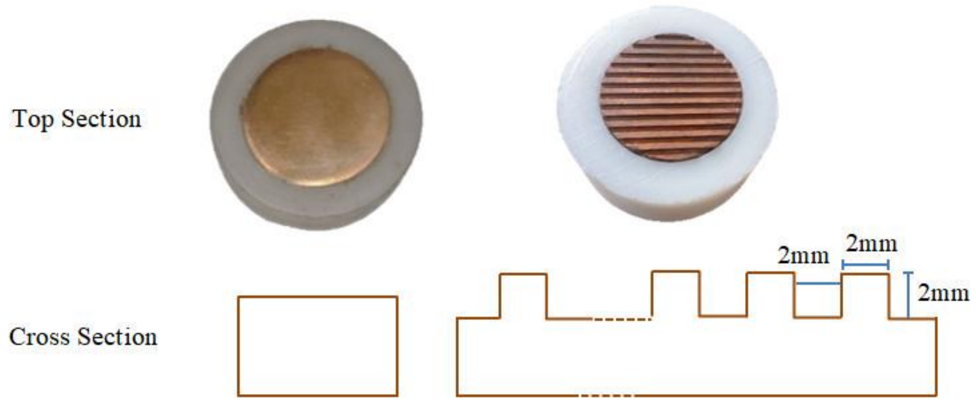

Figure 1: Electrodes Shape.

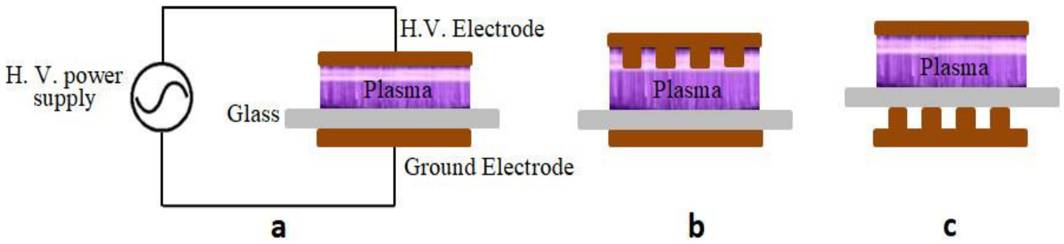

Figure 2: System Configurations.

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Results and discussion

The aim of studying the effects of electrode configurations and shapes is to understand how differences in electrode configurations influence the DBD plasma characteristics and performance; these properties can be determined by analysing the optical emission spectrum of the produced plasma. The optical emission spectrum of DBD plasma provides valuable information about the excited species present and their energy levels. However, the exact emission spectrum of DBD plasma can vary depending on several factors, such as gas composition, pressure, applied voltage, and the dielectric barrier material. The continuum emission arises from the excitation of electrons in the plasma, which subsequently collide with gas molecules, leading to radiation over a range of wavelengths. All obtained spectra are in the visible region. According to NIST data [19h], the spectral lines observed in the DBD plasma emission spectrum correspond to transitions between nitrogen energy levels, as nitrogen is present in the surrounding atmosphere. Figure 3 illustrates the spectra of the produced plasma for all designs of the DBD system. In this figure, the DBD plasma spectra show multiple peaks in the long UV region (300–400 nm), which are associated with N II atomic lines and molecular bands of N_2. The spectra varied with the electrode shape and system configuration; peak intensities also differed, with the highest intensity obtained when both electrodes were plane discs (Fig. 2a). This phenomenon is due to how the electric field distribution within the plasma is affected by the shape of the electrodes; the electric field is more homogeneous when using two plane disc electrodes.

Figure 4 shows the NII 380 nm peak distribution, where the full width at half maximum (FWHM) was determined by Lorentzian fitting, which estimates electron density at various configurations based on the Stark broadening effect. It can be seen that the full width varies with electrode

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arrangement due to variations in the electric field distribution.

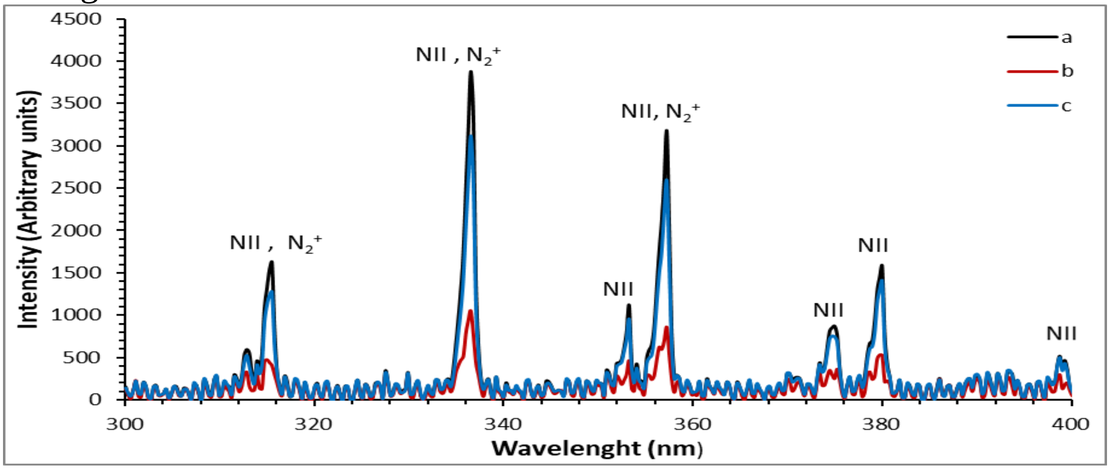


Figure 3: Spectrum of the discharge plasma for different configurations.

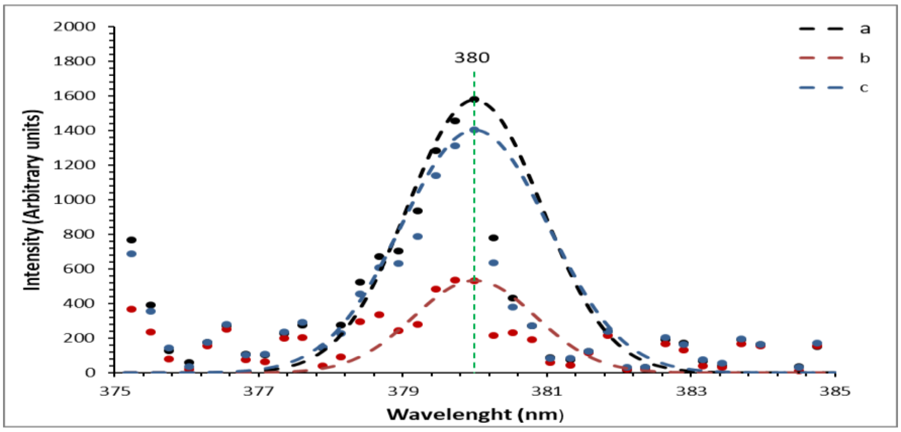


Figure 4: NII 380 nm peaks broadening and Lorentzian fitting at different configurations

The average kinetic energy of the electrons in the plasma is represented by electron temperature (T_e); in non-thermal plasma, electron temperatures are often substantially greater than the gas temperature. Electron temperature is estimated by plotting $\ln\frac{\varepsilon_{ji}\ \lambda_{ij}}{A_{ji}\ g_j}$ versus E_j and using equation 1 to compute the slope of the linear fitting of the resultant curve shown in Figure 5. The electrodes' geometry influences the plasma's electric field distribution; the electric field accelerates and heats the electrons, leading to an increase in their temperature. Different electrode shapes can alter the electric field strength, affecting electrons' energy transfer. Figure 5 illustrates Boltzman's method for calculating the electron temperature of plasma produced at different configurations of the DBD plasma system. In pattern (a), shown in Figure 2, the electron temperature of the plane disc electrode was 0.908 eV. In contrast, the highest electron temperature in pattern (c), the lowest temperature (0.89 eV), was obtained with pattern (b), in which one of the electrodes is a square zigzag disc serving as the high-voltage electrode.

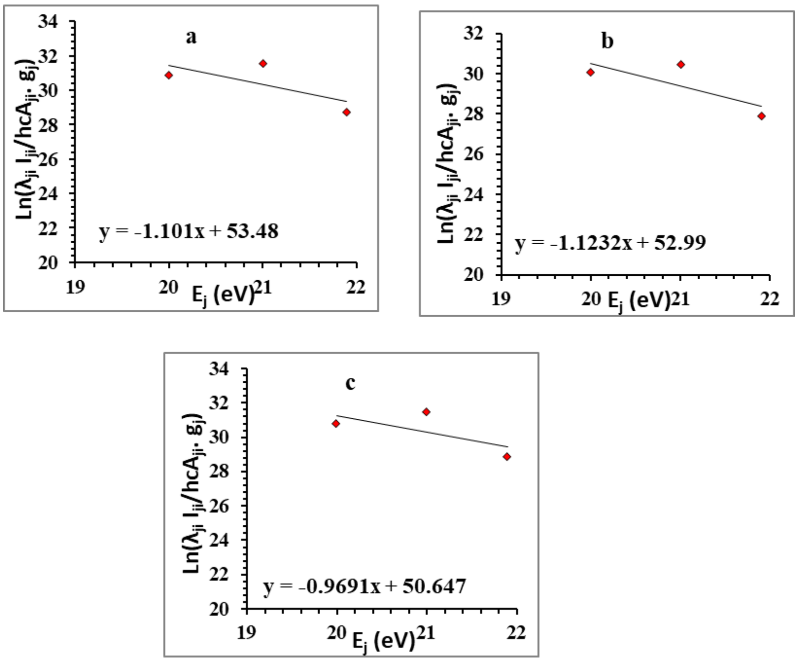
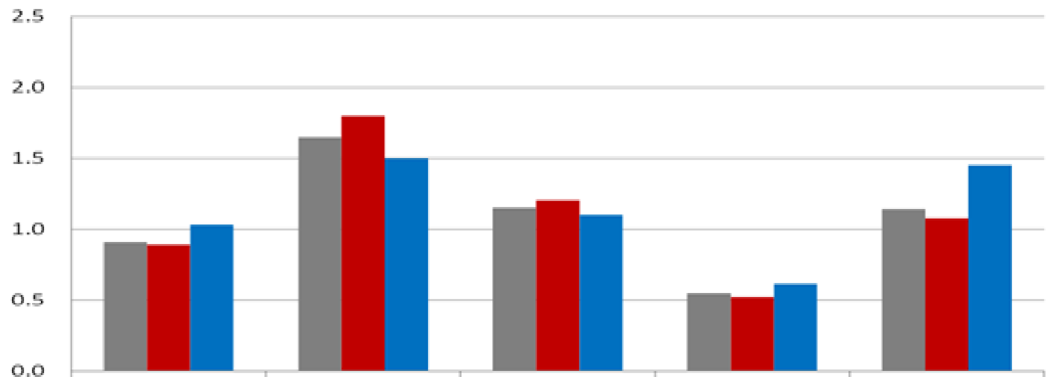


Figure 5: The dielectric shape effect on the DBD plasma temperature.

Electron density (n_e) refers to the number of electrons per unit volume in the plasma. Non-thermal plasmas can have electron densities ranging from 10^{15} to 10^{21} electrons per cubic meter; in the present study, the produced plasma in different electrodes configuration had an electron density of $(1.5-1.8)\times 10^{18}\text{cm}^{-3}$). The shape of electrodes influences the energy distribution of electrons in the plasma, where electrons gain or lose energy through interactions with the electrodes, and this energy transfer affects their mobility and collision rates with other particles. Consequently, the electrode shape-induced changes in electron energy distribution can affect the plasma density.

The electric field is non-homogenous and more intense at the sharp edges, which causes a disturbance in the electric field distribution in the gap between the electrodes and thus affects the nature of collisions between the components of the generated plasma, which in turn impacts the properties of the plasma. Plasma parameters electron temperature (T_e), electron number density (n_e), Debye length (λ_D), and plasma frequency (f_p), for all designs, are indicated in Figure 6; generally, the properties of the produced plasma are consistent with the properties of the non-thermal plasma.



	T_e (eV)	$n_e\times10^{18}$ (cm^{-3})	$f_p\times10^{12}$ (Hz)	$\lambda_D\times10^{-5}$ (cm)	$N_D\times10^{3}$
a	0.908	1.65	1.154	0.549	1.144
b	0.890	1.80	1.205	0.523	1.076
c	1.032	1.50	1.100	0.614	1.453

Figure 6: The dielectric shape effect on the DBD parameters.

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Conclusion:

The shape and arrangement of the electrodes play a crucial role in the properties of dielectric barrier discharge plasmas. The electrode shape contributes to determining the discharge type, especially if it includes sharp edges. The type of electrode (ground or high-voltage) also significantly influences the plasma mode, and consequently, both the temperature and density of the plasma electrons are important factors in determining the characteristics of the generated plasma. The presence of protrusions and sharp edges disturbs the plasma type generated, affecting its homogeneity and, therefore, its features. Such a work requires careful electrode design to achieve stable, durable non-thermal plasma systems.

To ensure optimal performance, smooth and polished electrode surfaces should be considered to minimize local electric field enhancement and prevent unwanted filamentary or arc transitions

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تأثير شكل القطب الكهربائي على خصائص بلازما تفريغ الحاجز العازل

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مستخلص البحث:
تعد تفريغات الحاجز العازل (DBD) مثالا نموذجيا على تفريغات الغاز غير الحرارية عند الضغط الجوي، والتي تتولد في تراكيب تتضمن مادة عازلة بين الأقطاب الكهربائية. يهدف هذا العمل إلى تعزيز فهم عمليات الانهيار وتكوين البلازما، وتأثير شكل الأقطاب الكهربائية وترتيبها على خصائص البلازما المتولدة. إذ يمكن لاختيار مادة الأقطاب الكهربائية وهندستها وترتيبها أن يؤثر على خصائص البلازما، مثل كثافة الإلكترونات وتوزيع طاقتها ودرجة حرارتها. يساعد فهم هذه الخصائص على تحسين البلازما لتطبيقات معينة. في هذا العمل تم دراسة ثلاثة أنواع من أنظمة بلازما DBD وذلك بتغيير شكل الأقطاب الكهربائية وترتيبها؛ أشارت النتائج إلى أن شكل الأقطاب الكهربائية وترتيبها يلعبان دورا أساسيا في تحديد خصائص البلازما.

الكلمات المفتاحية : بلازما حاجز العزل الكهربائي، بلازما غير حرارية، تفريغ التوهج عند الضغط الجوي(APGD) هندسة القطب الكهربائي، مطيافية الانبعاث البصري (OES)، معلمات البلازما، طريقة بولتزمان.

ملاحظة : هل البحث مستل من رسالة ماجستير او اطروحة دكتوراه ؟ نعم : كلا :
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