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Influence of Magnetic Mirror on the Emission Spectra of DBD Actuator

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Abstract
The research investigated the effect of magnetic mirror configuration on the properties of plasma formed in a dielectric barrier discharge (DBD) actuator under atmospheric pressure. The discharge was formed when a high alternating voltage of 22 kV at a frequency of 9 kHz was applied between the electrodes under atmospheric pressure. The magnetic mirror was created when two permanent magnets were placed behind the electrodes. Plasma emission spectra were detected using a photoemission spectrometer at different horizontal distances (D) between the dielectric and the actuator, ranging from 0 to 5 cm. The effect of the magnetic mirror on the plasma properties at different horizontal distances was studied. The results indicated that the value of electron temperature increases with an increase in the horizontal distance at a smaller rate in the presence of the magnetic mirror configuration. The decrease in the surface area of the electrode led to a significant increase in the electron number density in the presence of the magnetic field. The magnetic mirror affected the value of all the plasma properties studied. At the same time, there was no effect on the behaviour of plasma properties in the presence of magnetic mirror configurations.

Article Info.

Keywords:
Plasma Actuator, Magnetic Mirror, DBD, Plasma Parameters, Emission Spectra.

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1. Introduction
The domains of control sciences and thermo-fluid dynamics have shown interest in dielectric barrier discharge (DBD) plasma actuators [1]. Active airflow control through the use of plasma actuators has traditionally been studied to achieve boundary layer control [2, 3]. Plasma actuators have many applications, to name a few: boundary layer control [4], film cooling of turbine blades [5, 6], modulation of velocity fluctuations [7], separation control [8, 9], and weak control [10]. These gadgets possess highly intriguing characteristics, like rapid response time, effortless integration, extremely low weight, durability, lack of moving parts, and minimal power demands [11]. The DBD arrangement is currently the most extensively researched configuration of a plasma actuator.

The electrical discharge between two electrodes that are separated by an insulating dielectric barrier is known as a DBD. This extraction method has many applications, such as surfactants [12]. In this configuration of the plasma actuator, the two electrodes are typically copper plates, while the shielding is made of Teflon, Kapton, quartz crystals, or Mecor ceramics. The working principle of the plasma actuator is the electrohydrodynamic phenomenon of DBD and corona discharge, which occurs due to the transfer of ion momentum to neutral molecules by the shock process, representing the most common discharge in a plasma actuator [13]. Plasma actuators were first investigated by Roth et al. [14] in 2000. Since then, these actuators have been utilized in various applications. Numerous studies have examined the plasma created by this actuator, modified its structure to retain properties, and examined how parameters affect actuation efficiency. Saleh et al. [15] used DBD in a plasma system where the dielectric barrier was glass. AC voltage between electrodes, and a glass plate dielectric barrier produced non-thermal DBD Plasma. The study examined the impact of electrode type on DBD Plasma characteristics. Guo [16] studied aerodynamic plasma actuator concepts based on dielectric barrier discharge to increase their effectiveness in active control of flow. The study found that the third electrode affects the distribution of surface charges while the semiconductor surface facilitates their movement. Park et al. investigated the influence of a magnetic field produced by a permanent magnet in the perpendicular direction of the electric field on DBD performance [17]. Furthermore, another study by Taha et al. examined the contrast between the behaviour of DBD in the presence and absence of a magnetic field in the surrounding air. Their findings demonstrated distinct variations in various DBD characteristics, including discharge current, DBD plasma, power dissipation, and more, when the magnetic field was present compared to when it was absent [18]. When the pulse repetition frequency of a unipolar positive nanosecond pulsed DBD was lowered from 1200 to 100 Hz, the discharge became more homogeneous. Furthermore, an equivalent outcome can be attained in the presence of a parallel magnetic field [19].

The present work characterizes plasma actuator discharges that formed in single DBD with two AC frequencies and at different horizontal distances. The characterization encompassed many parameters such as I-V curve, electron temperature, electron number density, Debye length, and plasma parameter.

2. Theoretical Description of Plasma Parameters

This section provides a theoretical explanation of plasma parameters of DBD actuator, such as electron temperature (T_e), electron number density (n_e), Debye length (λ_D), plasma parameter (N_D). The T_e is the fundamental plasma parameter which is used to characterize the plasma state. The Boltzmann plot was employed in this study to determine the electron temperature as [12]:

$$I_{ji} = \frac{N(T)}{U(T)} g_j A_{ji} \frac{hc}{\lambda_{ji}} e^{-E_j/K_\beta T_e} \quad (1)$$

where: I_{ji}, λ_{ji} and A_{ji} are the intensity, wavelength and transition probability, respectively, corresponding to the transition from i to j, g_j is a statistical weight, h is Planck's constant, N(T) the number density of emitting species, c is the speed of light, U(T) is the partition function. The slope of this line corresponds to the magnitude of T_e (eV).

There are many methods to calculate the n_e; the Stark broadening method is used in this work [20, 21]:

$$n_e(cm^{-3}) = \left[\frac{\Delta\lambda}{2\omega_s}\right] N_r \quad (2)$$

where: ω_s is the electron impact, $\Delta\lambda$ denotes the line's full width at half maximum (FWHM), N_r is the reference electron number density, equals to 10^{16} cm^{-3} for neutral atoms and 10^{17} cm^{-3} for singly charged ions.

λ_D is a key property of the plasma that denotes its ability to inhibit external electric potential, which can be determined as [21-23]:

$$\lambda_D = 7430(kT/n)^{1/2} \quad m, T \text{ in } K^{\circ} \qquad (3)$$

The N_D represents the number of charged particles in the Debye sphere, which can be calculated as [21]:

$$N_D = n\frac{4}{3}\pi\lambda_D^3 = 1.38\times10^6\frac{T^{\frac{3}{2}}}{n^{\frac{1}{2}}} \quad (T \text{ in } K^{\circ}) \qquad (4)$$

where T_e is the electron temperature and n is the plasma number density.

3. Experimental Set up

Fig. 1 shows the experimental set-up of DBD actuator system used in this work. It consists of two rectangular aluminium electrodes (10×4cm) and a thickness of 0.7 cm, which are separated by an insulator, with different horizontal areas on opposite sides. The magnetic mirror configuration was formed by inserting two (4×2cm) rectangular magnetic permanents and of 0.5 cm thickness behind two electrodes, which are placed inside a rectangular Teflon container to prevent any electrical sparks generated at the edges of the electrodes. An AC high voltage power supply (22 kV) with an AC frequency of 9 kHz was supplied to the upper electrode (the powered electrode) while the lower electrode was grounded. The gap between the two electrodes was 0.8 cm. Pure epoxy (Euxit 50 KI) was used as the dielectric material and was mixed with hardener (Euxit 50 KII) at a 1:3 ratio for curing [24]. The dielectric's thickness was 0.3 cm. This work was established at room temperature under atmospheric pressure. Plasma was generated on the insulator's surface in the presence and absence of the magnetic field. Thorlabs compact spectrometer (Type CCS 100/M, made in Germany) was used to diagnose the emission spectra of the plasma generated on the dielectric surface at different horizontal distance between the dielectric and the DBD actuator. The spectrometer utilized has exceptional resolution, which is contingent upon the grating employed, and is capable of detecting wavelengths within the range of 320 to 740 nm. The magnetic field was measured by a Tesla meter (Leybold) with a value of 35.2 mT. The spectrometer was placed at an angle 45° with the direction of the magnetic field. The plasma parameters in the electrode gap were calculated by modifying the emission spectra of the plasma actuator using software from the NIST database. Ultimately, the shift in plasma with horizontal distances was captured by a high-resolution Samsung camera.

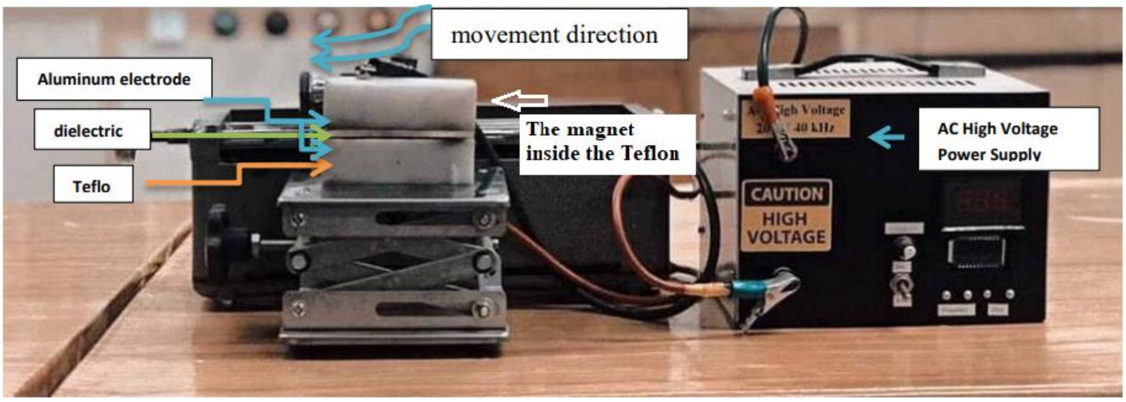

Figure 1: ***The DBD system set-up.***

4. Results and Discussion

4.1. Variation of Plasma with Horizontal Distance

Surface DBD plasma actuators are extensively studied because of their ability to control airflow. The primary benefits of these devices are their exceptionally rapid response time and low power usage. Many factors, such as the actuator's geometry (e.g., electrode shape, size, gap, and thickness), the power supply's electrical characteristics, the ambient gas, temperature, pressure, humidity, and ambient gas quality, and the physicochemical properties of the dielectric material, all have a significant impact on the discharge current's temporal progression. Fig. 2 shows a photograph of the plasma formed on the epoxy surface between the electrodes at different dielectric-actuator horizontal distances in the absence of the magnetic field. The data showed that when a high-voltage alternating current signal was applied, the filamentary streamers crossing the air gap were formed and propagated on the epoxy dielectric barrier surface. The density of the filamentary streamers formed in the air gap under atmospheric pressure decreased with the decrease in the electrode surface area of the powered electrode (i.e. an increase of the horizontal distance). This result agrees with those of Abd and Abbas [25]. Fig. 3 presents photographs showing the influence of the magnetic mirror configuration on the filamentary streamers formed in the air gap between the two electrodes of the DBD plasma actuator. It is clear that the presence of the mirror magnetic field caused an increase in the ionization in the air gap and, consequently, an increase of the density of filamentary streamers at all horizontal distances under study.

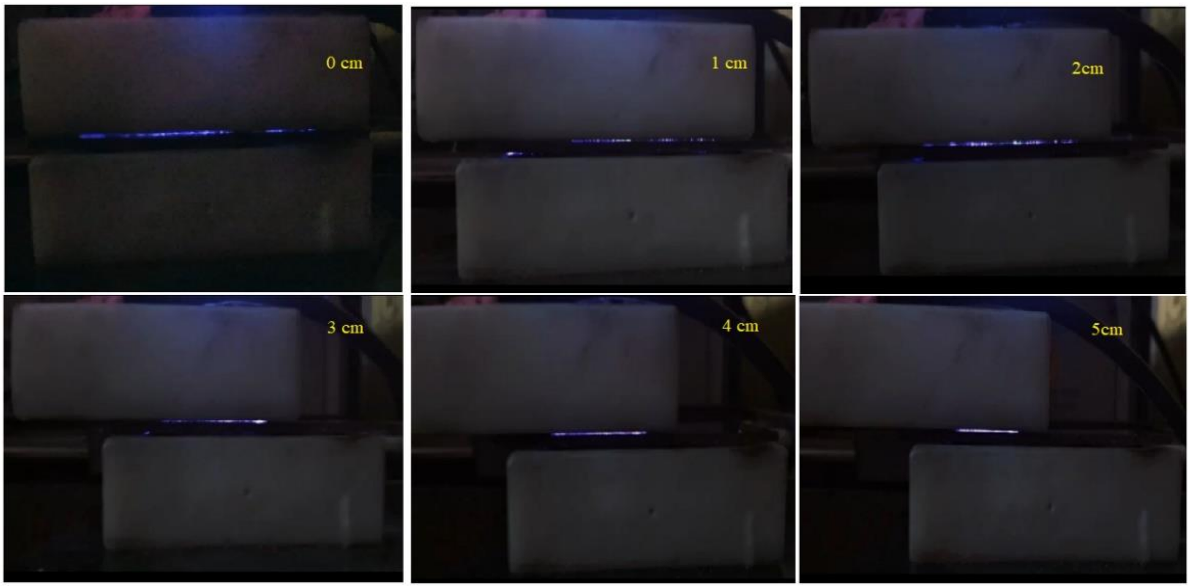

Figure 2: Influence of horizontal distance on the plasma formed in the DBD actuator in the absence of the magnetic field.

Figure 3: Influence of horizontal distance on the plasma formed in the DBD actuator with the magnetic mirror configuration.

4.2. Emission Spectra of Plasma

The Optical Emission Spectroscopy (OES) approach is frequently utilized for the diagnosis of the characteristics of DBD actuator with and without magnetic field. The emission spectra were acquired within the spectral wavelength range of 320 – 740 nm in the air gap between the electrodes under atmospheric pressure. Fig. 4 illustrates the emission spectra of the ionization of air in the electrode gap at different horizontal distances without a magnetic field.

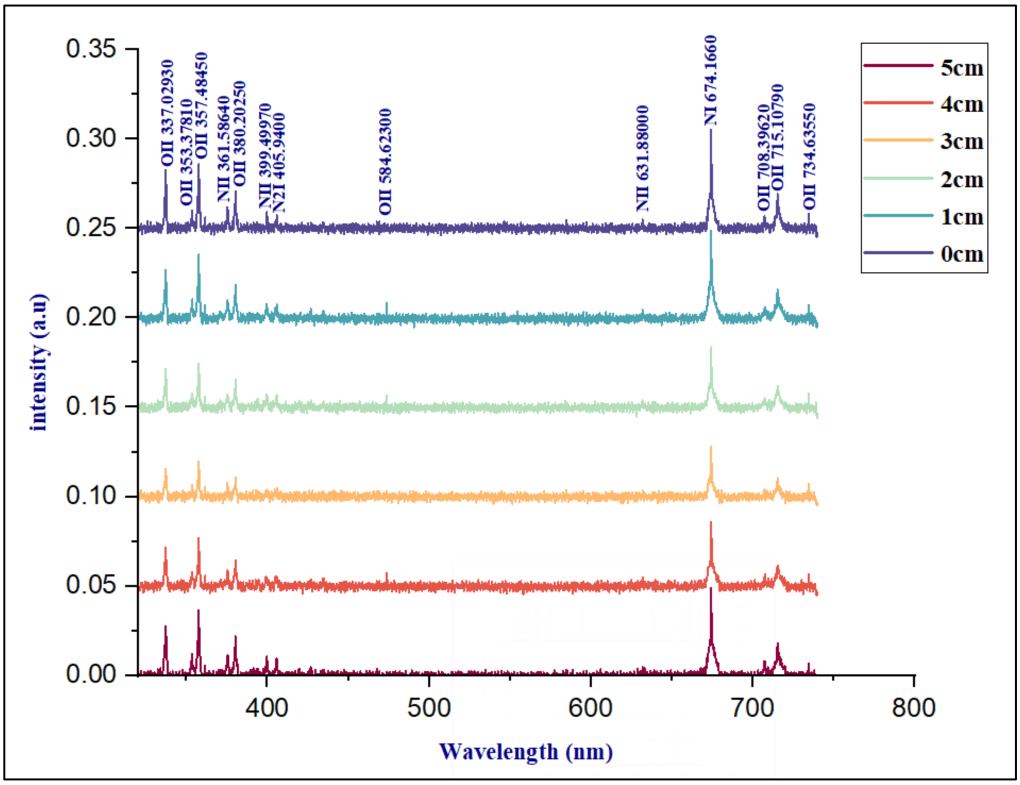

Figure 4: Influence of horizontal distance on the emission spectra in DBD actuator in the absence of the magnetic field.

The emission spectra show many oxygen (OII) ionic emission peaks at the wavelengths 337.023, 353.378, 357.485, 375.209, 380.203, 584.623, 708.396, 715.108 and 734.636 nm. One atomic emission peak of nitrogen (NI) appears at a wavelength of 674.167 nm. Another two ionic emission peaks of nitrogen (NII) were detected at wavelengths of 399.499 and 631.880 nm. There is also one molecular emission peak of nitrogen (N2I) corresponding to wavelength 405.940 nm. Increasing the horizontal distance, the spectra showed a decrease of the emission intensity. This behavior can be understood as follows: when the horizontal distance increases, the surface charge of the upper electrode (the powered electrode) is reduced because of the reduction of the surface area of this electrode. Therefore, reductions in the operational voltage of the plasma due to the surface charge lead to a notable decline in the actuator's performance. This result is in agreement with that of Abd and Abbas [25]. Finally, comparing Figs. 4 and 5 shows that the strength of the emission lines rises in the vicinity of a magnetic field. This phenomenon can be explained as follows: when a magnetic field is present, the magnetic force acting on the motion of the electron particle in the same direction as the electric field increases. As a result, the kinetic energy of the electron particle increases, leading to an increase in the discharge current. As a result, the micro-discharge exhibited greater spatial homogeneity between the electrodes. Thus, the excitation and photoemission processes are enhanced compared to the ionization situation, resulting in a brighter region above the one without the magnetic field [26].

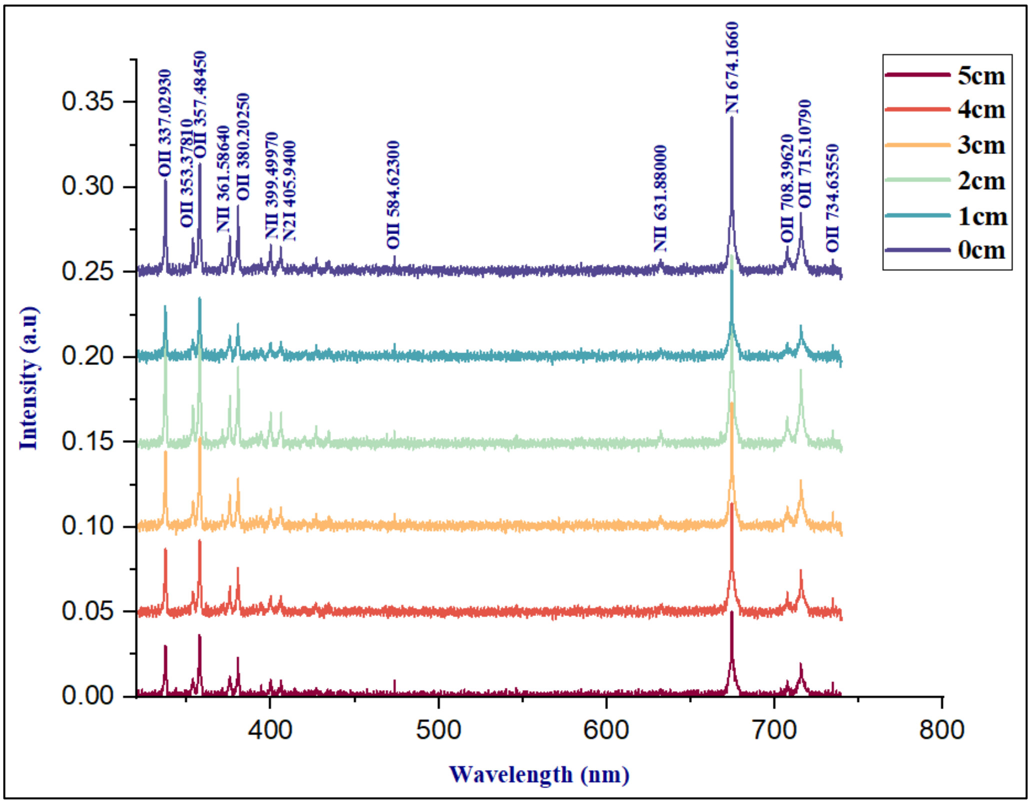

Figure 5: Influence of horizontal distance on the emission spectra in the DBD actuator in the presence of the magnetic field.

4.3. Influence of the Horizontal Distance on Plasma Actuator Parameters

T_e is the most important plasma characteristic that describes the plasma state. Under plasma thermodynamic equilibrium, the number of excited atoms follows the Boltzmann distribution to determine T_e. According to the Boltzmann plot method, the electron temperature was calculated with and without magnetic mirror configuration, as shown in Fig. 6.

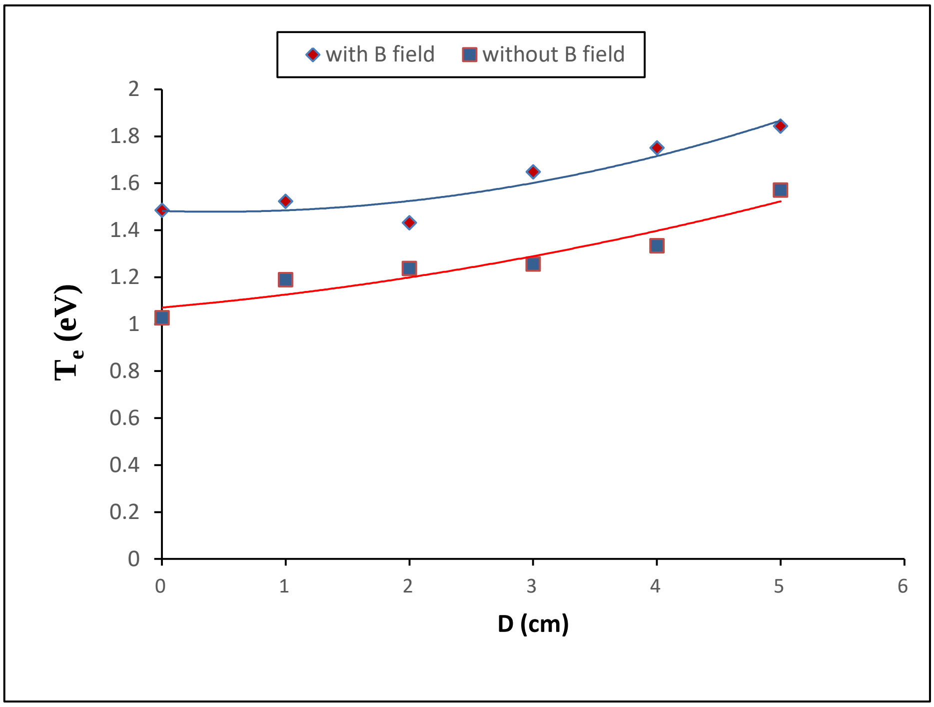

Figure 6: The variation of electron temperature with the horizontal distance with and without a magnetic field.

It can be noted that the value of T_e slowly increased with increasing the horizontal distance in the presence of the magnetic mirror configuration. The figure shows that the electron temperature rises when a magnetic field is present. This implies that the magnetic field can restrict the movement of electrons, decreasing their radial motion and enabling them to absorb energy from other sources more efficiently. As a result, the average kinetic energy of the electrons increases, leading to a higher electron temperature. The increase of T_e with the increase of D is due to the increase of the electric field strength within the plasma actuator with distance (D). Therefore, higher electric field strengths can lead to more energy transfer to electrons, increasing electron temperature.

The spectroscopic atomic lines released from the plasma are the most accurate method for estimating the n_e. Using the Stark effect for a wavelength of 380.298nm, the electron number density for the different horizontal distances (with ω_m =0.418 Å for peak λ=380.298nm) [27] can be calculated using Eq. (2) and plotted as shown in Fig. 7. From this figure, it can be noted that, without the magnetic field, the electron number density increases with increasing horizontal distance. When a magnetic field was applied parallel to the direction of the electric field, the decrease in the surface area of the electrode led to a significant increase in the electron number density. Additionally, the parallel magnetic field considerably increased the strength of reverse discharges revealing the reduction in electron surface dissipation. The parallel magnetic field decreased the number of the energetic electrons dissipating in the avalanche heads. These results are consistent with those reported by Abd and Abbas [25].

Fig. 8 illustrates the effect of the magnetic mirror on the variation of the Debye length (λ_D) with the horizontal distance (D) under atmospheric pressure in the plasma actuator. The Debye length decreases with the increase of the horizontal distance (D) in the presence and absence of the magnetic mirror, but at different rates. The data obtained in this study are in agreement with the results presented by Abd and Abbas [25]. The presence of the magnetic mirror caused a decrease in the Debye length value comparable to its value in the absence of the magnetic field. Consequently, this result means that the presence of the magnetic field reduces the effect of the space charge that accumulates on the surface of the dielectric in the electrodes gap. In addition, the plasma directed onto the surface of the insulator becomes wider in the presence of the magnetic mirror.

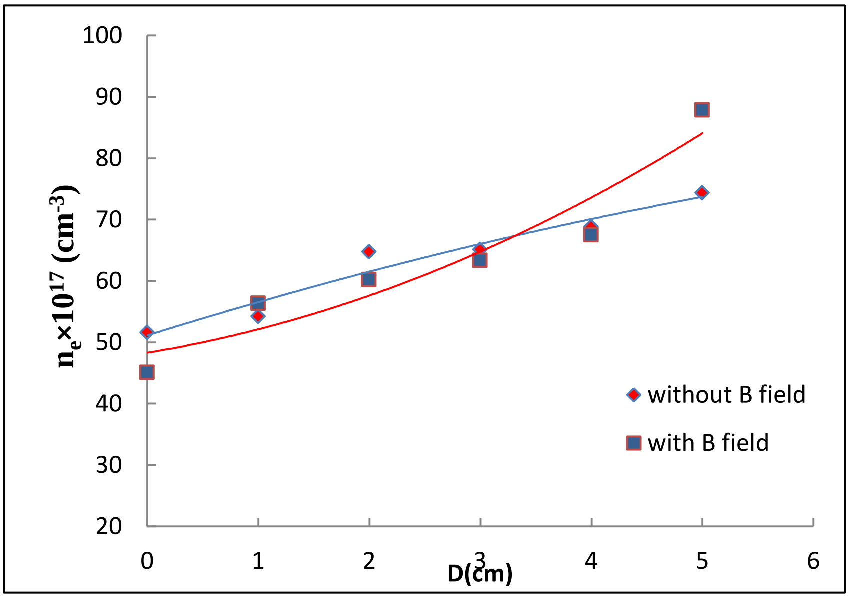

Figure 7: Variation of electron number density with moving distance at 9kHz frequency.

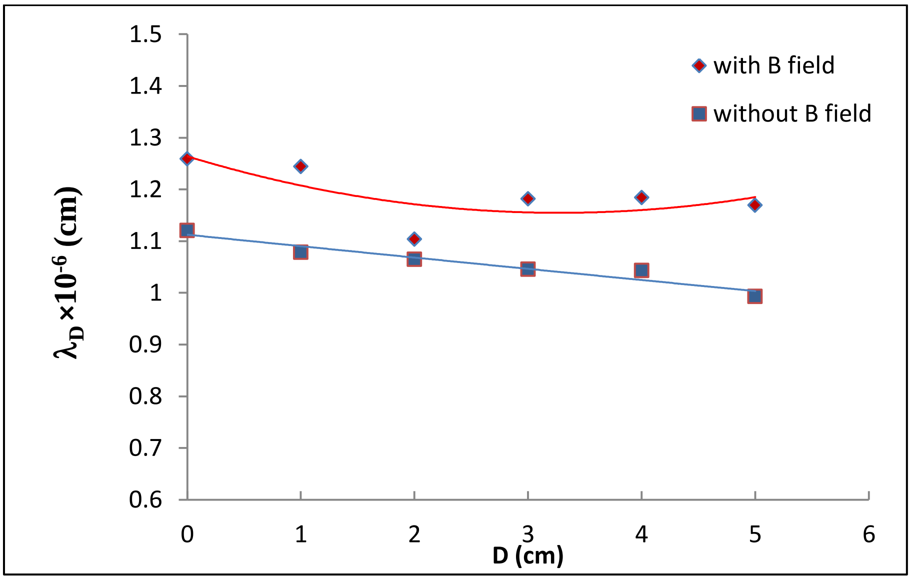

Figure 8: The impact of the magnetic field on the variation of λ_D with the horizontal distance under atmospheric pressure.

Finally, Fig. 9 demonstrates the impact of the magnetic mirror configuration on the variation of the number of charged particles in the Debye sphere as function of distance D. The results demonstrated that with and without magnetic mirror, the value of N_D showed a slight increase with the increase of the horizontal distance but at different rates. The magnetic field presence resulted in an increase in the quantity of charged particles due to an increase in ionization collisions. Comparing the results of the absence and presence of a magnetic field and for the discharge coefficients showed a slight effect of the dielectric barrier on the variation of N_D with D. These results are consistent with the results of Khaleel and Abbas [12]. Hence, it can be concluded that the magnetic mirror is responsible for the fluctuations in the plasma composition.

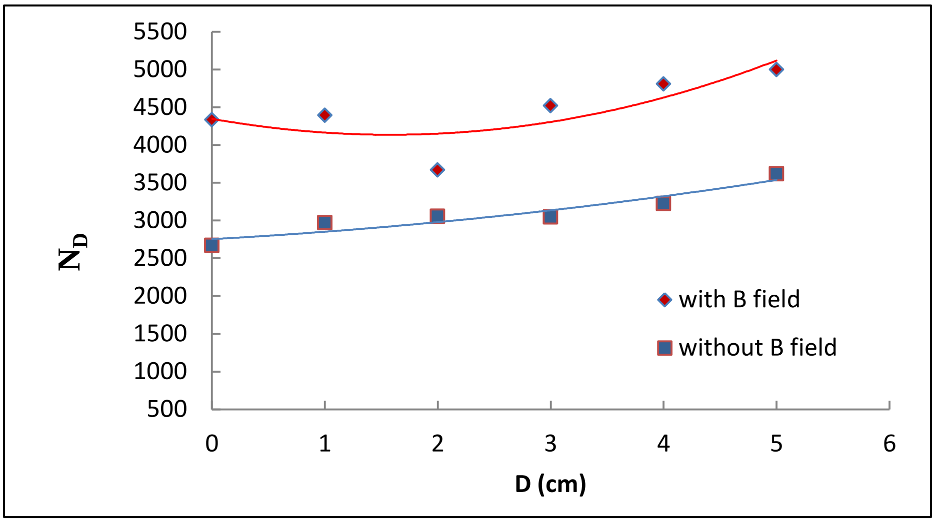

Figure 9: Influence of the magnetic field on the variation of N_D as a function of the horizontal distance at atmospheric pressure.

5. Conclusions

In the current work, the influence of the magnetic field configuration on the characteristics of the plasma actuator was investigated. The results detected a significant effect of the magnetic field on the variation of the plasma characteristics values with electrodes surface area. On the other hand, the magnetic mirror had no effect on the behavior of the plasma characteristics in the DBD actuator. All the plasma characteristics under study in the presence and absence of the magnetic mirror increased with the increase of the horizontal distance except for the Debye length, which showed a decrease in its value with the increase of the horizontal distance.

Conflict of interest

Authors declare that they have no conflict of interest.

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تأثير المرآة المغناطيسية على أطياف الانبعاث لمشغل DBD

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الخلاصة

تضمن هذا البحث دراسة تأثير تكوين المرآة المغناطيسية على خصائص البلازما التي تكونت في مشغل DBD (مشغل تفريغ الحاجز العازل) عند الضغط الجوي. يتشكل التفريغ عندما يتم تطبيق الجهد العالي المتردد البالغ 22 كيلو فولت بتردد 9 كيلو هرتز بين الأقطاب الكهربائية عند الضغط الجوي. تم إنشاء المرآة المغناطيسية عندما تم وضع قطعتين مغناطيسيتين دائمتين خلف الأقطاب الكهربائية. تم الكشف عن أطياف الانبعاث البلازمي باستخدام مطياف الانبعاث الضوئي على مسافات أفقية مختلفة تتراوح بين 0 إلى 5 سم. تمت دراسة تأثير المرآة المغناطيسية على خواص البلازما عند مسافات أفقية مختلفة. أشارت النتائج إلى أن قيمة درجة حرارة الإلكترون تزداد مع زيادة المسافة الأفقية (D) بمعدل أقل في وجود تكوين المرآة المغناطيسية. بينما يؤدي انخفاض مساحة سطح القطب إلى زيادة كبيرة في الكثافة العددية للإلكترونات في وجود المجال المغناطيسي. وكان للمرآة المغناطيسية تأثير على قيمة جميع خواص البلازما المدروسة. وفي نفس الوقت لا يوجد أي تأثير على سلوك خواص البلازما في ظل وجود تكوينات مرآة مغناطيسية.

الكلمات المفتاحية: مشغل البلازما، المرآة المغناطيسية، مشغل تفريغ الحاجز العازل، معاملات البلازما، أطياف الانبعاث.