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The Influence of the Magnetic Field on the Plasma Characteristics in Hollow Electrodes Discharge System

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Abstract

This work is an experimental study about the effects of gas pressure and magnetic field on plasma characteristics produced in an internal hollow electrodes discharge (HED) system. The results show that the breakdown voltage values increase with increasing the working pressure (especially with the presence of a magnetic field). The breakdown voltage depends on the p.d. product, where p is the gas pressure and d is the distance between the electrodes. While the values of current discharge decrease with the increase of the working pressure. The temperature of electron and the number density of electron are calculated from the Boltzmann method and the broadening of Stark, respectively. The results showed that the electron number density (n_e) and plasma frequency (ω_{pe}) increase with increasing the gas pressure, especially with the presence of a magnetic field, i.e. the plasma is more stable with the presence of magnetic field. While the electron temperature (T_e) and Debye length (λ_D) decrease with increasing the gas pressure.

Keywords: Hollow electrodes discharges (HED), I-V characteristics, Breakdown voltage, magnetic field, OES, electron temperature, electron number density.

تأثير المجال المغناطيسي على خصائص البلازما في نظام تفريغ الأقطاب المجوفة

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الخلاصة

في هذا العمل، أجريت دراسة تجريبية حول تأثيرات ضغط الغاز والمجال المغناطيسي على خصائص البلازما الناتجة في نظام تفريغ الأقطاب المجوفة الداخلية. أوضحت البيانات أن قيم جهد الانهيار تزداد مع زيادة ضغط العمل (خاصة مع المجال المغناطيسي). يعتمد جهد الانهيار على حاصل ضرب pd، حيث P هو ضغط الغاز و d هي المسافة بين الاقطاب. بينما تقل قيم تيار التفريغ مع زيادة ضغط العمل. تم قياس درجة حرارة الإلكترون و الكثافة العددية للألكترون من طريقة بولتزمان و توسيع ستارك، على التوالي. أظهرت النتائج أن الكثافة العددية للألكترون وتردد البلازما تزداد مع زيادة ضغط الغاز، خاصة مع تطبيق المجال المغناطيسي، أي أن البلازما أكثر استقرارًا مع وجود المجال المغناطيسي. بينما تقل درجة حرارة الإلكترون وطول ديباي مع زيادة ضغط الغاز.

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Introduction

Hollow electrodes discharge (HED) is used to generate glow discharges of high intensity. The distribution of plasma and the model depends on the shape and size of the electrodes used (especially the cathode), and one is related to the other. Many different forms of cathodes are known as hollow cathodes. All hollow cathodes are thermionic devices that depend on the ionization of a neutral gas by electron bombardment to generate plasma [1]. Hollow cathodes discharge (HCD) are divided into two major groups: conventional hollow cathode (CHC) and modified hollow cathode discharges (MHC). The HCD was characterized by cathode surfaces in their conventional form (planar, cylindrical, spherical or other geometry) containing negative glow while the anode was placed outside the discharge cavity [2]. The discharge develops in various modes in a conventional HCD, depending on the discharge current, each with a distinct voltage-current (I-V) characteristic. Dixon et al. (2014) [3] investigated low pressure hydrogen HCD, mode transition in a radio frequency (rf) by a change in total light emission and different expansion structures. The hollow anode discharge (HAD) polarity in a DC discharge is such that the plasma potential is always positive with respect to the anode in order to repel the excess electron flux due to its spontaneous thermal motion that arrives at the anode [4]. Compared to the cathode area, the anode area in these plasma sources is small enough, so they are referred to as a constricted source of plasma anode [5]. In (2005), Gleizer et al. [6] worked to optimize hollow-anode low-pressure electrical discharge for generating high-current electron beams. The results on the designer's optimization of the electron beam source caused by a ferroelectric surface discharge of a high-current electric discharge hollow-anode (HA) was reported. The breakdown voltage of a gas discharge is a function of the product of gas pressure and the distance between electrodes. If the value of pd is large, very small number of ions reaches the cathode surface to produce the secondary electrons, thereby, increasing V_B. If the value of pd is small, the number of ionizing collisions of electrons between the electrodes is greatly reduced and therefore V_B increases [7, 8]. The plasma discharge regions are compressed with increasing the working pressure. The glow discharge intensity in the region between the two electrodes is nonhomogeneous which increases in the region near the surface of the electrodes [9].

In order to determine plasma parameters such as electron temperature (T_e), electron number density (n_e), Debye length (λ_D), and plasma frequency (ω_{pe}), optical emission spectroscopy (OES) has been used. The Boltzmann plot method is a simple and widely used for spectroscopic measurement, especially for measuring T_e [10]. Boltzmann distribution is satisfied in case of local thermodynamic equilibrium [11].

$$\mathrm{Ln}(\lambda_{mn} I_{mn}/g_m A_{mn}) = -E_m/kT_e + \mathrm{Ln}(N/U) \tag{1}$$

Where: I_{mn} , λ_{mn} and A_{mn} are the intensity, wavelength and transition probability, respectively, corresponding to transition from m to n, g_m is a statistical weight, h is Planck's constant, N is the number density of emitting species, c is the speed of light, U is partition function.

The Stark broadening effect was used to calculate n_e which requires a line free from self-absorption [12]:

$$n_e(\mathrm{cm}^{-3}) = [\Delta\lambda/2\omega_s]\, N_r \tag{2}$$

Where: $\Delta\lambda$ is the full width at half maximum of the line, and ω_s is the theoretical line full-width Stark broadening parameter, which is calculated at the same reference electron density $N_r = 10^{16}(cm^{-3})$.

Plasma frequency can be given as [13]:

$$\omega_{pe} = \sqrt{\frac{n_e\, e^2}{m_e\, \varepsilon_0}} \tag{3}$$

Where: ε_0 is the permittivity of free space, m_e is the mass of the electron and e is the charge of the electron.

Debye's length can be calculated by the formula [13]:

$$\lambda_D = \sqrt{\frac{\varepsilon_0\, k_B\, T_e}{e^2\, n_e}} \cong 69\sqrt{\frac{T_e\, (°K)}{n_e\, (m^{-3})}} \cong 743\sqrt{\frac{T_e\, (eV)}{n_e\, (cm^{-3})}} \tag{4}$$

Where: k_B is Boltzmann's constant.

Experimental part

Figure 1 illustrates the DC hollow electrodes discharge (HED) chamber used in this work. The vacuum chamber was a cylindrical Pyrex glass with a length of 37cm and a diameter 30cm. Two small pipes connected at the mid-top and bottom of the chamber; one was linked to pumping systems, while the other was used to supply the argon gas (99.9% purity). The chamber was evacuated by two stages rotary pump (CIT-ALCATEL Annecy, made in France) to a base pressure of 2×10^{-2}Torr. A permanent magnet of a value of 3.4mT (measured with a digital tesla meter made by Brolight Company, Model: BEM-5032, made in China), located behind the cathode electrode, was used for the confinement of plasma. Digital Pirani gauge (type Edward, made in England) was used to measure the pressure of the chamber from atmospheric to the base pressure of the vacuum system. The hollow electrodes usually have a cylindrical geometry and are made from aluminum with an inner diameter and inner length of 6 and 3cm, respectively. Both electrodes are fixed by Teflon to prevent any connection with the chamber walls; and the distance between the two electrodes was 8cm.

The working principle of this device is the glow discharge between the electrodes. In this device, a normal glow discharge was produced when a DC constant voltage of about 4kV was applied between the two electrodes. Due to this external voltage, the argon plasma discharge was formed, and then the voltage of the electrodes dropped. Images were taken for the glow within the plasma under different conditions (different gas pressure in two cases with and without magnetic field) with a high-resolution digital camera (canon model). The emission intensity of discharge regions in this system was analysed using the image J software. The emission spectrum emitted from the plasma was detected by the optical emission spectrometer (model Thorlabs, made in Germany) to determine plasma characteristics by diagnostics of the spatially integrated plasma light emissions for a wavelength range of 320-740nm. The spectrometer was placed at an angle of 45^0 from the plasma column. The results of the spectrum of this system were calibrated with NIST database software to calculate the plasma characteristics in the inner region of the cathode electrode.

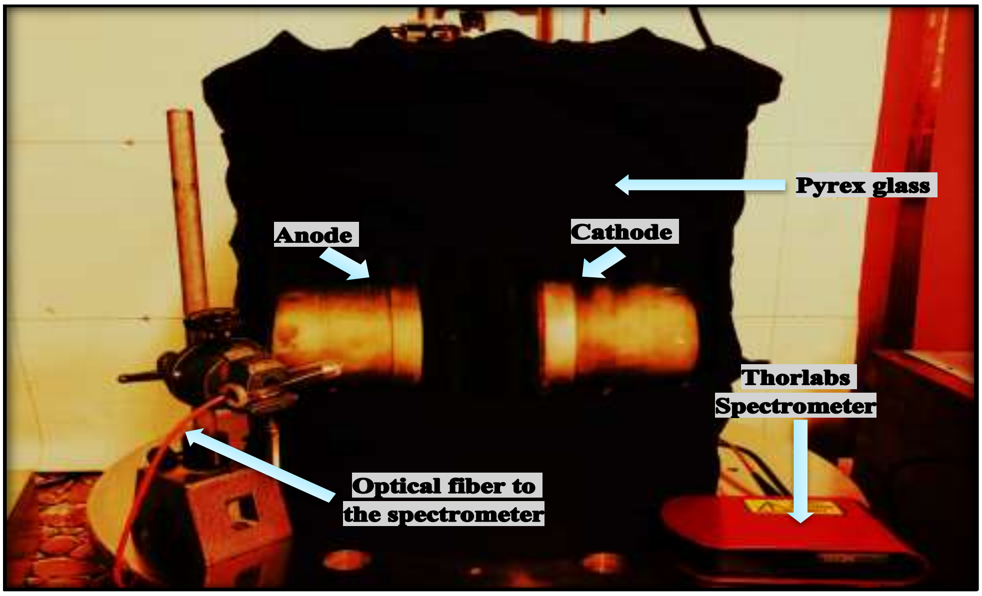

Figure 1: The hollow electrodes discharges (HED) chamber.

Results and discussions

Figure 2 demonstrates the variation of the breakdown voltage as a function of pd, in two cases, with and without a magnetic field (B). Many features can be obtained from this figure; the breakdown voltage curve has the same form as Paschen's curve form in both cases. The minimum value of pd was shifted toward the high-pressure region in the presence of the magnetic field: while the breakdown voltage values increased. This increase is caused by the increasing effect of the space charge due to the plasma confinement. While the shift of the Pd_{min} value in the presence of the magnetic field can be explained as follows: the probability of the inelastic collisions of energetic electrons with argon atoms increased with the presence of the magnetic field, and this probability increased with the increase of gas pressure [8]. This result agrees with that of Eichhorn et al. [14].

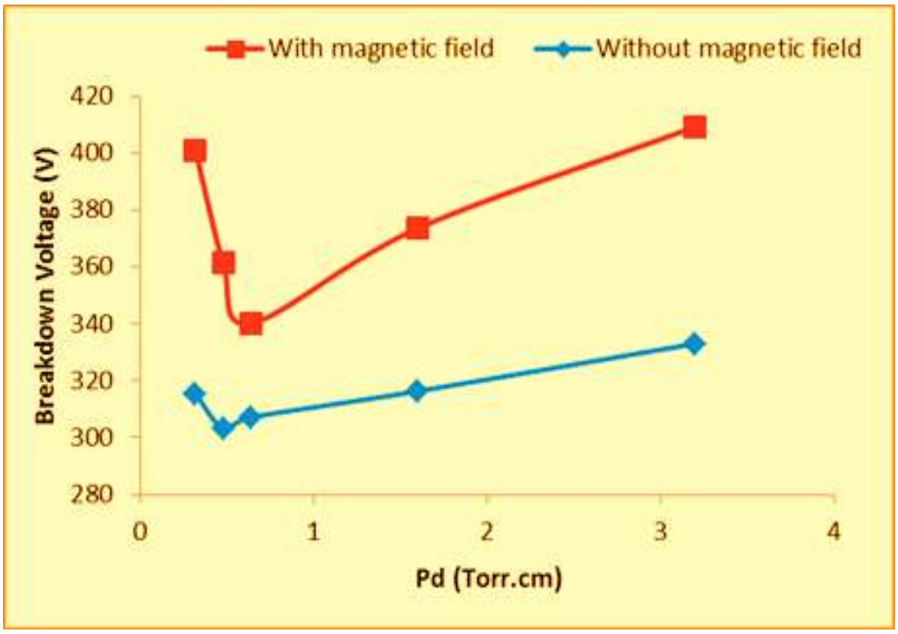

Figure 2: The breakdown voltage for Argon gas V_B as a function of pd, with and without B.

The variation of the discharge current with gas pressure with and without magnetic field (B) can be noted in Figure 3. The two curves detected that the current discharge decreased with the increase of gas pressure in both cases. The discharge current decreases steadily from 6.72 to 6.55mA and 5.86 to 5.83mA and then decreases sharply from 6.55 to 5.78mA and 5.83 to 5.52mA with and without the magnetic field, respectively. This means that high pressure increases the number of electrons collisions with argon atoms preventing electrons from accessing sufficient energies for ionization between successive collisions [7]. The values of the discharge current in the presence of the magnetic field are larger than those in its absence. The increase of inelastic electron collisions in the presence of the magnetic field confinement was the cause of arising of ionization processes [7].

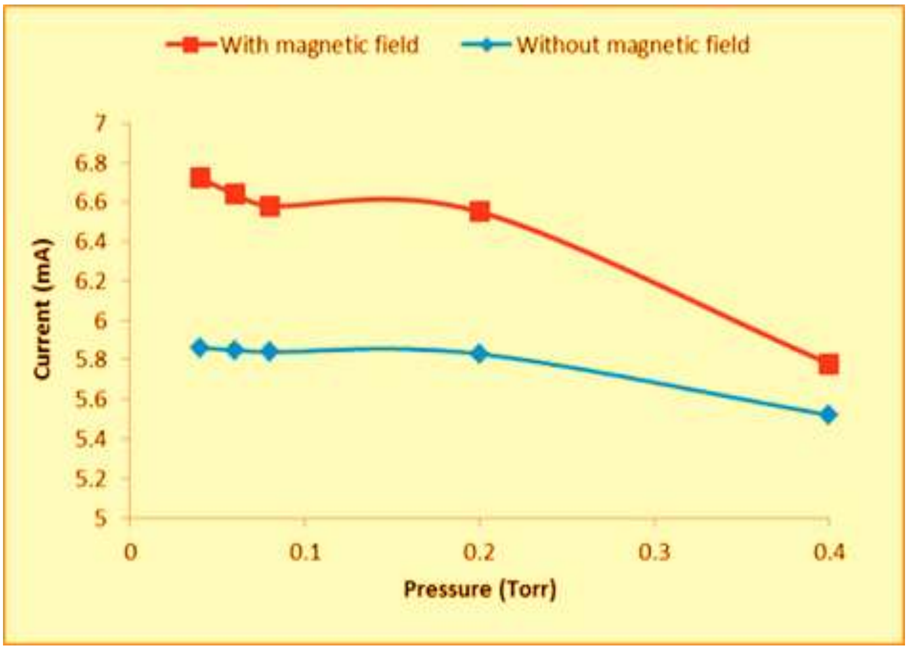

Figure 3: Current –Pressure curves, with and without magnetic field.

Figure 4 shows the influence of the magnetic field on the I-V in hollow electrodes discharges (HED) system. I-V curves have decreased with increasing gas pressure from 0.04 to 0.2Torr in both cases, with and without the magnetic field, due to the increase of the electron number density, which causes more ionization collisions; hence, I-V curves decrease which essentially depend on n_e [15]. The increase of the voltage values with the magnetic field is because the presence of the magnetic field causes plasma confinement in a strong electric field region and enhances the negative space charge near the anode. Therefore, the voltage curves with the magnetic field are higher than those without it [15].

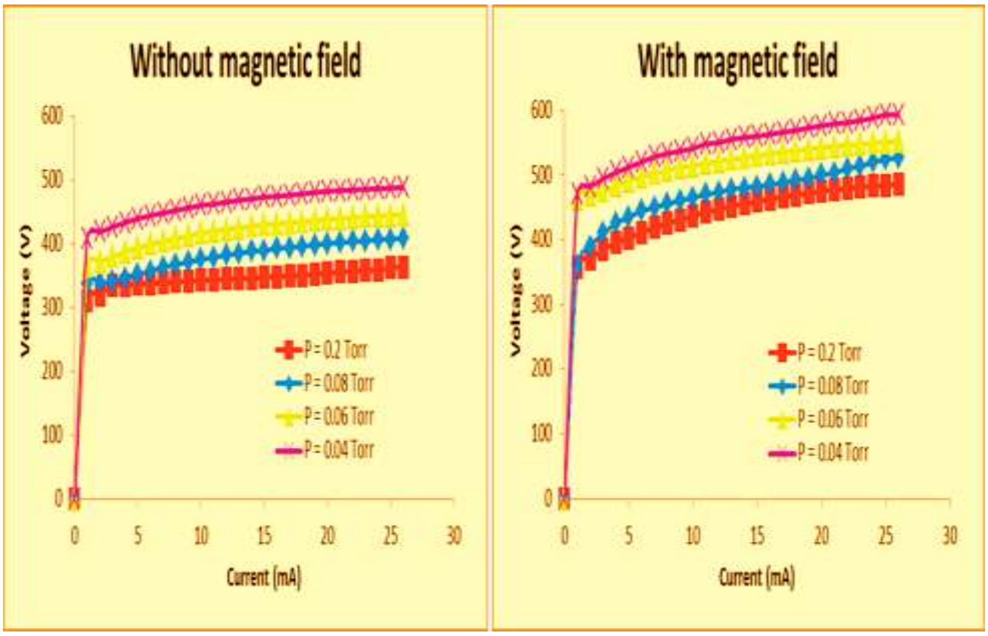

Figure 4: I –V curves of Argon gas for HED, with and without B.

Figures 5 and 6 demonstrate the influence of increasing the argon pressure on the glow discharge regions between the two electrodes in hollow electrodes discharges (HED) system, using a direct applied voltage of about 4kV at different working pressures (0.04, 0.06, 0.08 and 0.2Torr) in two cases, with and without magnetic. It can be observed from Figure 5 that in the absence of the magnetic field, when the pressure increases, the cathode regions (cathode fall) are compressed, the negative glow becomes a thin layer of intense luminosity, while the positive column and anode fall increase [16]. Because the mean free path of electrons is inversely proportional to the gas pressure, it follows that the distance required for an electron to travel before it produces adequate ionization to sustain the glow is also inversely proportional to the pressure. Then, the thickness of the cathode dark region decreases as the pressure is increased (i.e., the cathode fall is compressed). Consequently, the negative glow region becomes a thin layer of intense luminosity and the positive column region and anode fall increase. Electrons follow helical paths around the magnetic field lines so undergoing more ionizing collisions with Ar atoms near the hollow cathode. Because the transverse direction of the B will bend the paths of most electrons that have relatively high speed to the cathode surface and enable them to produce the necessary ionization to maintain the discharge while moving a shorter distance along the axis in the cathode dark region. Thus, the length of the cathode dark region is reduced [17].

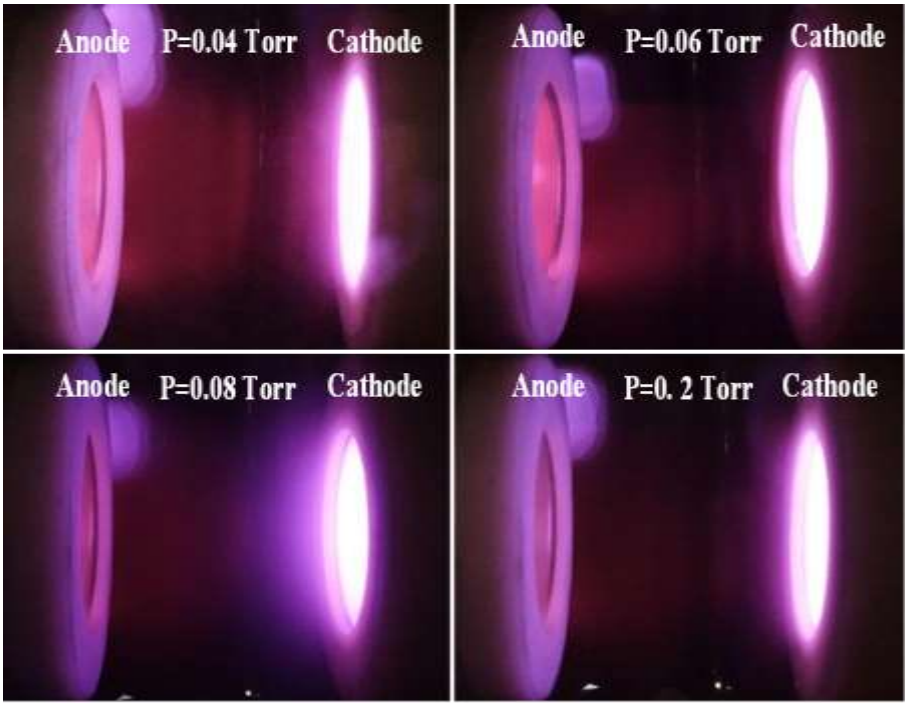

Figure 5: The influence of Argon gas pressure on the glow discharge regions for HED system, without B.

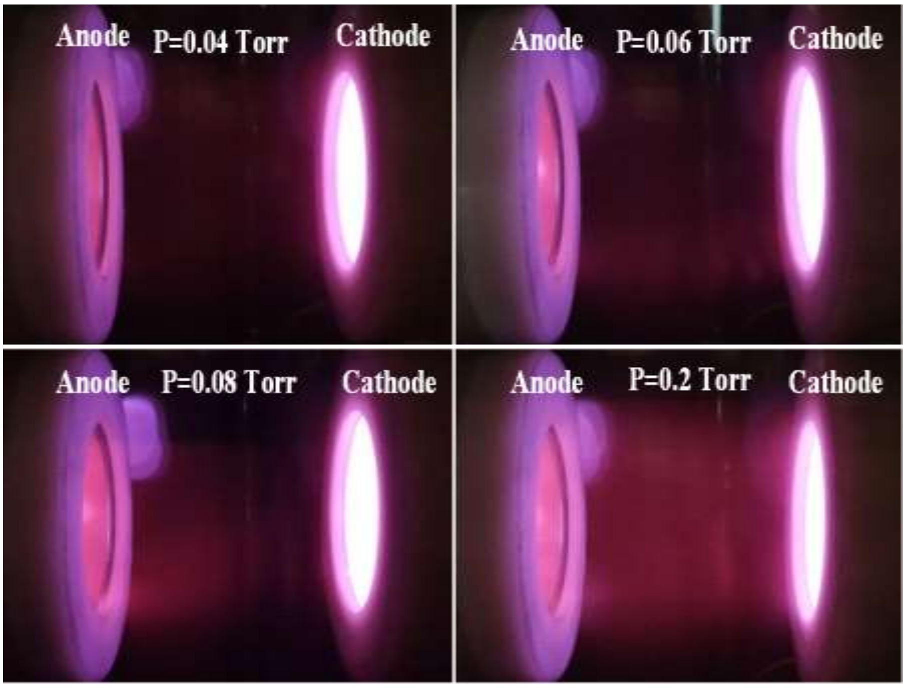

Figure 6: The influence of Argon gas pressure on the glow discharge regions for HED system, with B.

Figures 7 and 8 represent the emission light intensity distribution in the gap between the two hollow electrodes in both cases of presence and absence of the magnetic field. Without the magnetic field, it was observed that the emission intensity reduced with increasing the gas pressure from 0.04 to 0.2Torr. Because the increase of gas pressure causes an increase in the inelastic collision of electrons with Ar atoms. Therefore, the internal electric field decreases, reducing the effect of space charge, which causes a decrease in the light emission intensity [18]. On the other hand, the presence of the magnetic field causes the emission intensity to increase with the increase of gas pressure. Because the magnetic field boosts the effect of the space charge, as a result of plasma confinement in the region of a strong electric field, this will increase the kinetic energy of the ionizing electrons of argon atoms. Thus, the light emission intensity increases with the increase of gas pressure [19].

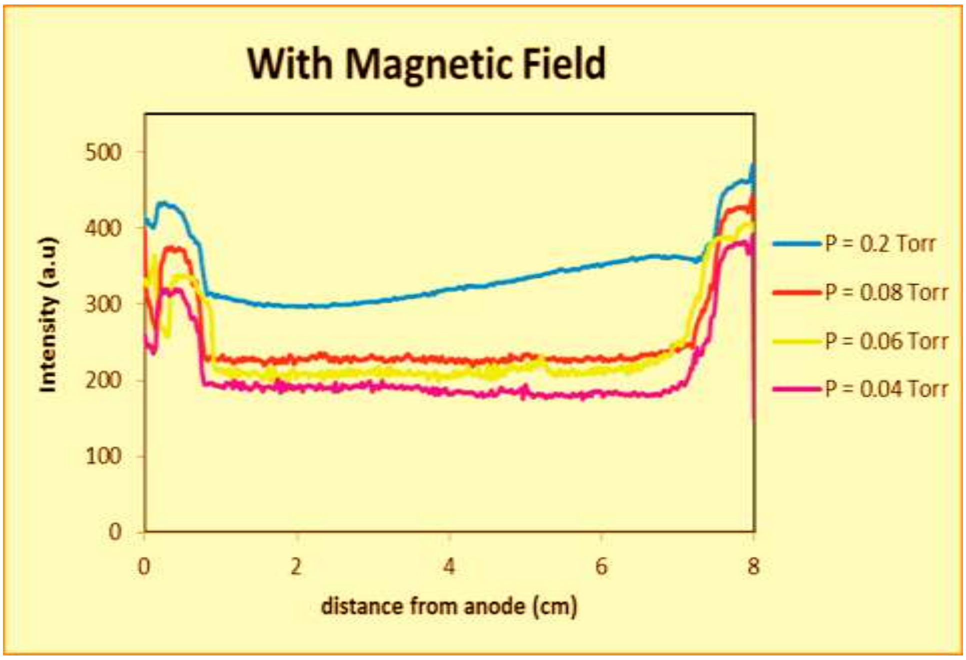

Figure 7: The difference of intensity against distance from anode, with B.

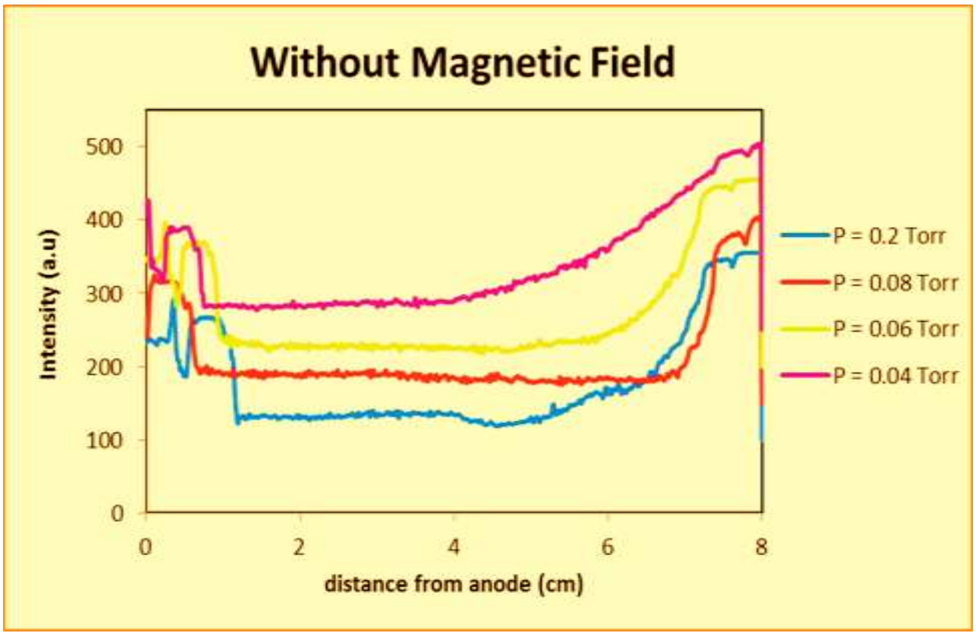

Figure 8: The difference of intensity against distance from anode, without B.

The emission spectrum of argon plasma in hollow electrodes system at different working pressures (0.04, 0.06, 0.08 and 0.2Torr) with and without magnetic field is shown in Figure 9. It can be noted that there are many peaks of the neutral ArI atom at the wavelengths 337.347, 389.466, 427.2169, 454.4746, 462.8441, 476.8673, 545.1652, 594.0855, 603.2127, 675.2834, 706.8735, 715.8839 and 735.0814nm. The atomic emission lines of N2I also appear at the wavelengths 357.69, 375.54, 399.84, 435.5 and 654.48nm. All peaks intensity increases with increasing the gas pressure from 0.04 to 0.2Torr, due to the increase of the density of the atoms hence increasing the collision's probability between the electrons and gas atoms, which allows electrons to have enough energy for excitation. On the other hand, the magnetic field causes a decrease of electrons mean free path, which results in a decrease of the emission intensity of the plasma spectrum [20].

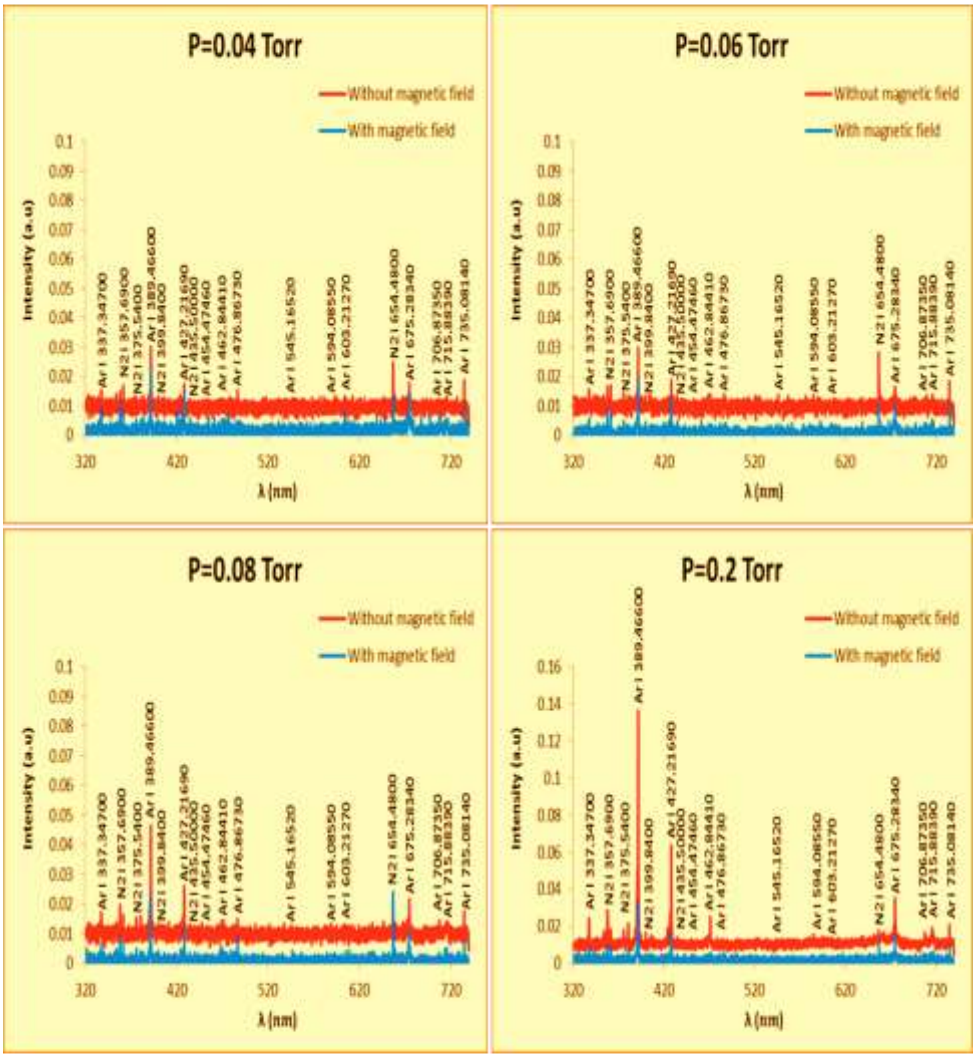

Figure 9: The optical emission spectra of Argon plasma at different working pressures, with and without B at an internal of HED.

The electron temperature (T_e) represents one of the most significant parameters used to characterize the plasma state. The determination of T_e is important to comprehend the excitation, dissociation and ionization processes taking place in the plasma. By plotting $\mathrm{Ln}(\lambda_{mn} I_{mn}/g_m A_{mn})$ versus upper energy level (E_m), T_e was calculated from the slope of the best line. This requires peaks that originated from the same atomic species with data from NIST site. One of the most reliable techniques to determine the electron number density (n_e) is using atom and ion spectral lines emitted from the plasma. The electron density is calculated from the Saha-Boltzmann, Equation (2). The plasma frequency (ω_{pe}), which relates to the electron number density, can be calculated by Equation (3).

The Debye length (λ_D) represents the shielding distance or the thickness of the plasma sheath and can be calculated from Equation (4) [21].

Table 1: ArI standard lines which were used to calculate electron temperature, and their characteristics [22]

$\lambda(nm)$	$A_{ji} * g_i$	E_i(eV)	E_K(eV)
476.86730	**$4*10^6$**	**12.90701519**	**15.5062612**
603.21270	**$2.21*10^7$**	**13.07571560**	**15.13054424**
675.28340	**$9.65*10^6$**	**12.90701519**	**14.74254073**
706.87350	**$6.0*10^6$**	**13.09487245**	**14.84836887**
715.88390	**$2.1*10^6$**	**13.28263891**	**15.0140654**
735.08140	**$1.2*10^6$**	**13.32785693**	**15.0140654**

Figure 10 represents the effect of the B on the behavior of the electron temperature (T_e) with gas pressure. The data shows that T_e decreased with the increase of gas pressure from 0.04 to 0.2Torr in the presence and absence of the magnetic field. The decrease in T_e with pressure is twofold; first, it decreases sharply from 0.922 to 0.614 eV and then decreases steadily from 0.614 to 0.481eV. As a result of the transfer of electron energy to the gas atoms, the gas temperature increased while the T_e and the average kinetic energy of electrons decreased. In addition, in the presence of the magnetic field, the temperature of the electron increased compared to its value in the absence of the magnetic field. Because the magnetic field confines the plasma in the region of a strong electric field, this confinement causes an increase in the energy of the electrons [21].

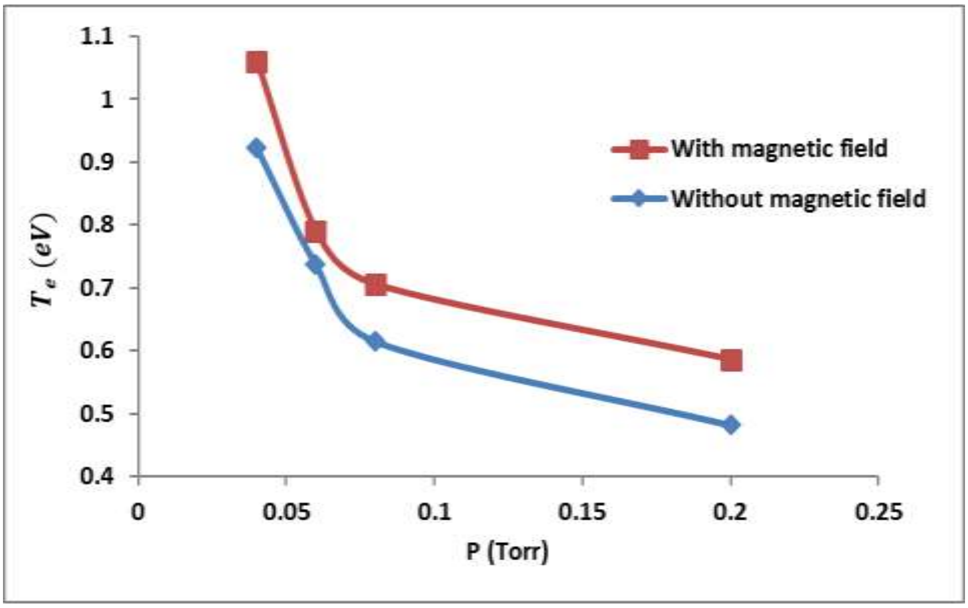

Figure 10: The difference of (T_e) against the gas pressure with and without B at an internal of HED.

Figure 11 illustrates the influence of the magnetic field on the behavior of electron number density (n_e) with Ar gas pressure. One can observe that n_e increases with the increase of the gas pressure. The electron number density increased from 3.954 $\times 10^{15}$ to

$4.134\times10^{15}cm^{-3}$. While with the magnetic field, n_e increased from 4.138×10^{15} to $4.548\times10^{15}cm^{-3}$. Increasing the gas pressure leads the plasma to be confined in a small volume and hence increasing the collisions between electrons and argon atoms (i.e., the results of plasma density with magnetic field are higher than that without magnetic field) [23].

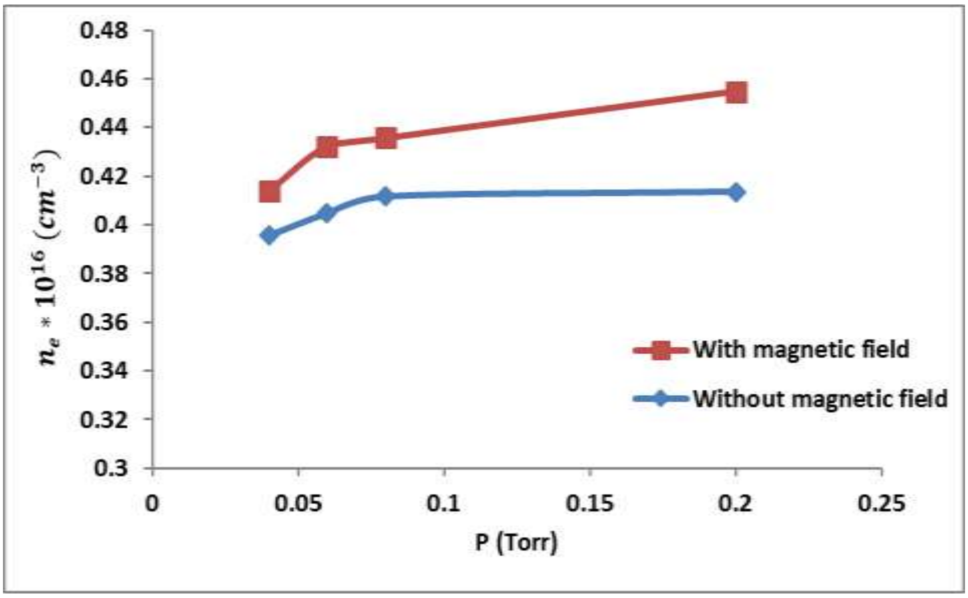

Figure 11: The difference of (n_e) against the gas pressure with and without B at an internal of HED**.**

Figure 12 demonstrates the variation of plasma frequency with working pressure in two cases, with and without magnetic field. It can be noted that the values of plasma frequency increased with increasing the gas pressure in both cases with a higher rate in the presence of the magnetic field. In its absence, the plasma frequency increased from 35.544×10^{11} to 36.344×10^{11}rad/sec. while with the magnetic field, the plasma frequency increased from 36.358×10^{11} to 38.118×10^{11}rad/sec.

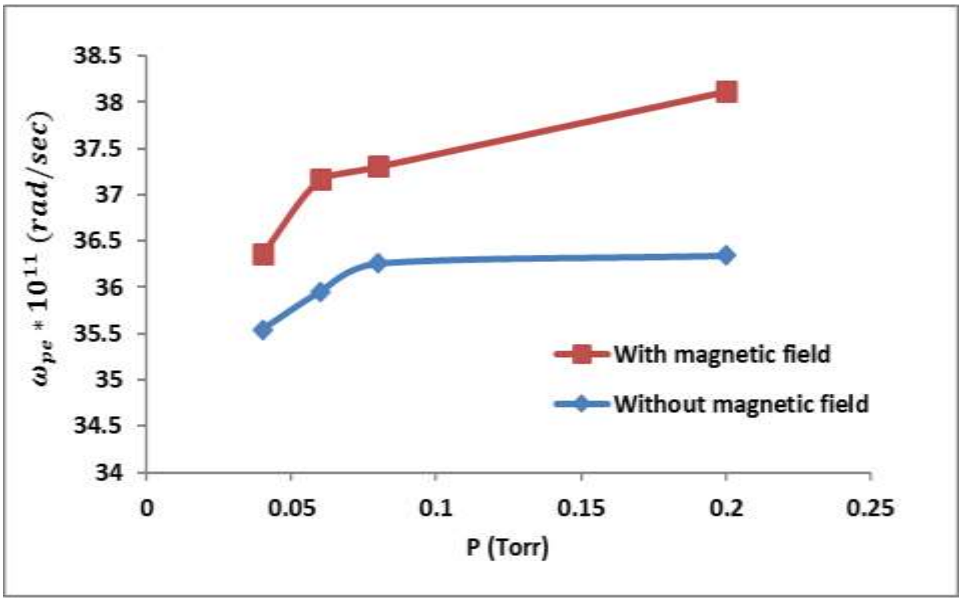

Figure 12: The difference of (ω_{pe}) against the gas pressure with and without B at an internal of HED.

In addition, the variation of Debye length with the working pressure in both cases, with and without the magnetic field was plotted, as shown in Figure 13. It was noted that the Debye length decreased from 11.348×10^{-6} to about 8.016×10^{-6}cm with increasing the working pressure from 0.04 to 0.2Torr in the absence of the magnetic field. On the other hand, the presence of the magnetic field caused a reduction in the Debye length from 11.896×10^{-6}cm to 8.435×10^{-6}cm with increasing the gas pressure. These behaviors mean that the increase of $n_e$with the increase of the gas pressure gives lower Debye length. Consequently, the thickness of the cathode sheaths was reduced. This effect generates a greater plasma volume. The presence of the magnetic field causes a reduction in the plasma volume as a result of the confinement phenomena [24].

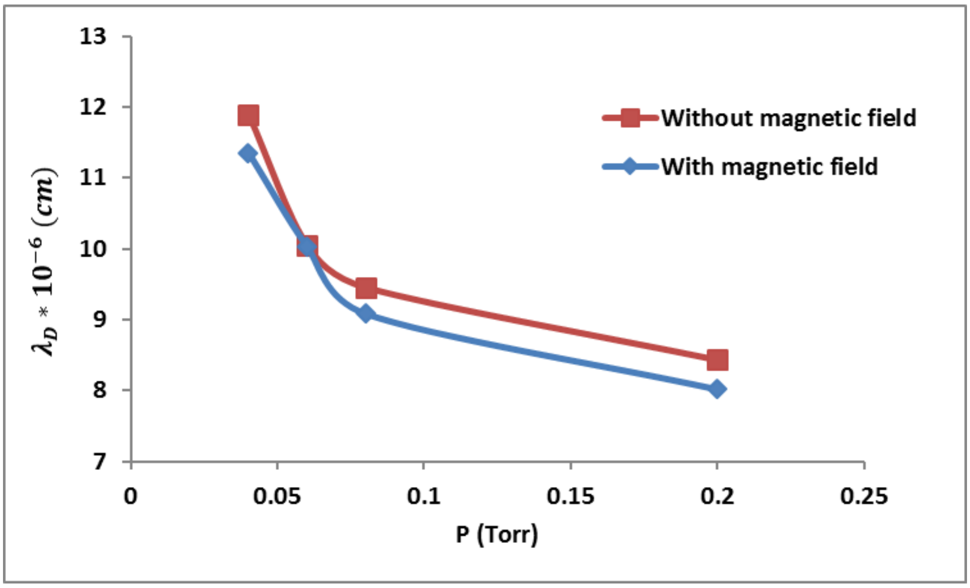

Figure 13: The difference of (λ_D) against the gas pressure with and without B at an internal of HED.

Conclusions

In this work, it was shown that when the magnetic field was applied to the plasma, the values of the breakdown voltage of the gas increases due to the increasing concentration of ionizing electrons. While the values of current discharge decrease with the increase of gas pressure. In the absence of the magnetic field, it was observed that the emission intensity is reduced with increasing the gas pressure. While with the magnetic field, the emission intensity increases with the increased gas pressure because the magnetic field boosts the effect of the space charge due to plasma confinement in the region of a strong electric field. In addition, the effects of working pressure and magnetic field on the properties of the plasma were illustrated. The present results showed that the electron temperature and Debye length decrease with more gas pressure, while the number density of electrons and plasma frequency increase. As well as, the electron temperature and its density with magnetic field are higher than those without magnetic field due to an increase in plasma confinement.

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