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Magnetic Field Effect on the Characteristics of Large-Volume Glow Discharge in Argon at Low Pressure

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Abstract

The magnetic field effect on the current-voltage characteristic curves of glow discharge in argon at low pressures has been experimentally investigated. The electrical discharge was ignited in a stainless steel tapered chamber of a nominal volume of $0.5m^3$ immersed inside a water-cooled coil capable of delivering a magnetic field of strength B of up to 0.42T. Three water-cooled electrodes were inserted into the chamber up to a point where their tips were 20cm away from the surface of the central column of the chamber. An enhancement of the electric field configuration within the region of the electrode assembly was performed by threading one of the electrodes with stainless circular discs(80mm and 140mm in diameter) in various forms(attached or separated). Depending upon the experimentally operating conditions, different glow discharge voltages and their corresponding currents were recorded with an optimum current of 10A at B= 500G and P= 10^{-3} mbar. A discharge current of 11.7A was reached as the gas pressure was raised by an order of magnitude at B=10G at d=20cm with very slight changes in the discharge voltage. Experimental results were found to be sensitive to the geometry of the electrode assembly, P, and B. Elevation of cathode surface temperature was recorded and found effective in reducing the pumping down cycle over a process of glow discharge cleaning of the internal chamber surface.

Keywords: Large-volume discharge, Magnetized argon plasma, Glow discharge.

تأثير المجال المغناطيسي على خصائص تفريغ التوهج كبير الحجم لغاز الاركون تحت ضغط واطئ

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الخلاصة

يتحقق البحث عمليا من تأثير المجال المغناطيسي على المنحنيات الخصائصية للتيار – الفولتية في توهج غاز الاركون تحت ضغوط واطئة. استخدمت لاحتواء هذا التوهج حجرة معدنية مصنوعة من الحديد غير قابل للصدا حجمها التقريبي 0.5 متر مكعب. غمرت الحجرة بمجال مغناطيسي تصل شدته الى 0.42 تسلا يولده ملف نحاسي مبرد بماء يجري خلاله لتجنب التاثيرات الحرارية. استخدمت اقطاب ثلاثة مبردة ايضا، ادخلت للحجرة بحيث كانت الزاوية بين كل قطبين متجاورين 120 درجة وطرف كل قطب يبعد 20 سم عن العمود المركزي للحجرة. ولغرض تعزيز شدة المجال الكهربائي استخدمت اقراص معدنية مختلفة الاقطار تحيط بالاقطاب لتقليل البعد بين كل قطب والسطح الداخلي للحجرة وبترتيب منفصل او متصل مع بعضها البعض للحصول على مجالات كهربائية مختلفة في شكلها الهندسي. تولدت في التفريغ الكهربائي تيارات بقيم مثلى وصلت الى 10 امبير تحت مجال مغناطيسي شدته 500 جاوس وضغط غاز مقداره 10^{-3} ملي بار. لقد اوجدت التجارب امكانية تسجيل قيم للتيار وصلت 11.7 أمبيرعند مضاعفة قيمة الضغط مرتبة واحدة وتحت تأثير مجال مغناطيسي مقداره 10 جاوس في موقع حافة الاقطاب، اي على بعد 20 سم من العمود المركزي.

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تشير هذه النتائج الى اعتماد المنحنيات الخصائصية للتوهج في هذا الحجم الكبيرعلى الشكل الهندسي للمجال الكهربائي وضغط الغاز وشدة المجال المغناطيسي في موقع اطراف الاقطاب. برهنت هذه التجارب ايضا على امكانية استخدام التوهج الكهربائي لتنظيف سطوح حجر الفراغ الكبيرة وتقليل دورة الفراغ وذلك بسبب ملاحظة ارتفاع درجة حرارة الحجرة لتأدية هذه المتطلبات.

Introduction

A glow discharge (GD) is generated when a sufficient potential difference is applied across two electrodes in a chamber containing a gas at low pressure. It is, therefore, a stage following the electrical breakdown of a gas when its atoms are ionized after gaining sufficient energy via collisional processes leading to the formation of GD-plasma [1]. Because of their distinctive features and physical characteristics, GDs have found a wide area of applications in science, technology, and industry [2]. To meet the requirements of functionally efficient application, GDs have been extensively studied throughout a number of approaches and techniques depending on the mode of glow designated by the region within its current-voltage characteristic curve and the area of application. Theoretical modeling, computer simulation, and experimental investigations have been carried out aiming at a good insight into the discharge processes and more understanding of the various associated physical parameters and their behaviour under certain conditions with or without applying an external magnetic field to the discharge [3, 4]. As laboratory plasma source of unique physical characteristics, GDs of gases have been used for more than five decades over a vast area of technological applications ranging from vacuum electronics to steel industry. Experiments with complex (dusty) plasma devices carried out with GD modes have also been of great interest since they establish a cornerstone for understanding the formation of strongly-coupled systems and dust-driven nonlinear phenomena [5].

Depending upon the basic plasma field of research and specific engineering problems, typical literature involving GDs may be presented in three groups. The first group is concerned with the various characteristic parameters involved in the operational conditions such as electrode geometry, gas type and pressure, dimensions of containing vessel where no external effect exists. Typical studies [6, 7] under certain gas pressure and discharge-generating source showed that the current-voltage curves and other spectroscopic measurements may describe the behaviour of GD plasmas and their associated features. Other experiments investigate the effects of the cathode parameters and geometry of the plasma-containing vessel on electron temperature using argon as plasma-forming gas and spectroscopic tools of diagnostics [8, 9].

The sparking parameter, electron energy, and ionization processes were included in other experimental studies [10].The main objective of the second group emphasizes on specifically scientific research and engineering applications of GDs under various conditions. This scheme covers high current switches for pulsed power technology[11], shock wave propagation in diffuse plasma [12], radiation emission sources and discharge lamps[13, 14], GD processing for semiconductor deposition and surface modification[15, 2], pseudo discharges and nitrogen plasma parameters[16] and chaotic current oscillations for studying active media of gas lasers[17].

The third group may designate the effect of an externally-applied magnetic field on the breakdown conditions and GD plasma parameters in various gases. The effect of the magnetic field strength on both electron density and temperature was studied in air, hydrogen, and argon in relatively small discharge vessel [18]. The results showed that the electron temperature decreases and the radial electron density increases for longitudinal magnetic field exceeding 1000G in argon while this density diminished and the electron temperature increased under transverse magnetic field of strength reaching 150G in air and less in hydrogen and argon. In another study [19], the Paschen minimum voltage was found to be reduced from 315V to about 310V in argon GD as a longitudinal magnetic field strength was raised from zero to 350G over a pressure range (0.05-0.1) mbar with electrode spacing adjusted from 4cm to 8cm in glass tube of 30cm in length and 13cm in diameter. The effect of the magnetic field was also investigated in a “macro” hollow cathode discharge in argon [20]. Current-voltage curves were deduced at pressure range of (1-10) mbar under a magnetic field strength of 1T. Although the discharge current was relatively low (few milliamperes), the hollow cathode fall was found to decrease with increasing this current.Limited experimental studies have been found concerning GD of argon contained in large-volume metallic vacuum chamber immersed in a magnetic field. The present study which may be categorized within the third group describes GD experiments carried out in a large-volume stainless steel chamber of circular cross section similar to those used in magneticallyconfined plasma experiments. However, the selection of such experimental configuration follows the fact that tapered metallic vacuum chambers with such dimensions are commonly used in ion sources where glow discharge cleaning(GDC) of the internal surface of the chamber is practically essential to reduce the pumping down cycle. The GD in the present experiments was ignited in argon at low pressure and the effect of an externally-applied magnetic field on the current-voltage characteristic curves was thoroughly investigated when the geometry of the electric field was modified and discharge currents, higher than those discussed above, were recorded with their corresponding applied voltages. The process of (GDC) is usually performed by charged particles bombardment and the flow of such relatively high currents through the discharge circuit over certain periods of time.

Theoretical Background

Any theoretical treatment of dc glow discharge of gases at low pressure may start with considering the correlation between Paschen parameters and Townsend coefficients. The main equations which can be written in the framework of such correlation describe the ionization of the gas atoms by collisional processes and the associated resulting parameters.

In general, the electrical discharge of a gas can be described by the empirical equation [21, 22]:

$$\alpha = aP\exp\left[-\frac{bP}{E_d}\right] \quad \textbf{(1)}$$

Where α is the first Townsend coefficient which represents the number of ionization events performed by a moving electron in a path length of 1cm along the discharge electric field E_d, a and b are two empirical constants, and P is the gas pressure.

When the electric field is uniform, its magnitude can be written as the ratio between the discharge voltage V_d and the electrode separation r, i.e.,

$$E_d = \frac{V_d}{r}$$

A condition for having a self-sustaining discharge may be written as follows [22]:

$$\exp(\alpha r) = \frac{1}{\gamma} + 1 \quad \textbf{(2)}$$

Where γ is the second Townsend ionization coefficient.

It can be stated that the voltage V_d depends upon the gas, cathode material, electrode spacing and the pressure.

By considering Eqs (1) and (2), the following interpolated explicit equations can be deduced

$$V_d = \frac{b(Pr)}{c+\ln(Pr)}$$

$$\frac{E_d}{P} = \frac{b}{c+\ln(pr)}$$

$$c = ln\frac{a}{\ln(\frac{1}{\gamma}+1)}$$

It can be noticed that both V_d and $\frac{E_d}{P}$ depend on the product (Pr); r being a general dimension of distance, from which the importance of the sparking parameter may be realized in glow discharges. Moreover, the dependence of the Paschen coefficients a and b on the gas must be via the collision cross section between electrons and ions and c via the Townsend coefficient $\frac{E_d}{P}$.

Experimental Technique

These GD experiments were carried out in a stainless steel vacuum chamber of a nominal volume of about $0.5m^3$ (180 Cm in dimeter). The chamber was slightly tapered and it had six rectangular openings; two of them were fitted to the ducts of a vacuum system and the other four were closed by flanges designed to allow the electrode insertion, viewing, gas feeding, and electrical connections. Such design allowed the use of three electrodes through the centers of three flanges around the circumference in such a way that the angle subtended between each two electrodes is 120^0. These electrodes, each of 1.0 m in length and 2cm in diameter, were made of stainless steel and they were water-cooled to avoid any possible heating effect resulting from the discharge current. A central column which had been machined as a part of the chamber structure was taken as a reference surface to define a relevant distance (not thee electrode spacing) between the electrode tips and the internal surface of the chamber which was electrically at earth potential (under certain circumstances the electrode spacing could have been less than d). All the three electrodes were threaded into the flanges through Teflon insulating bushings with O-ring arrangement to maintain electrical insulation and they could be moved to and away from the central column of the chamber. A schematic diagram of the experimental setup including the electrode-chamber assembly and electrical circuit is shown in Figure-1.

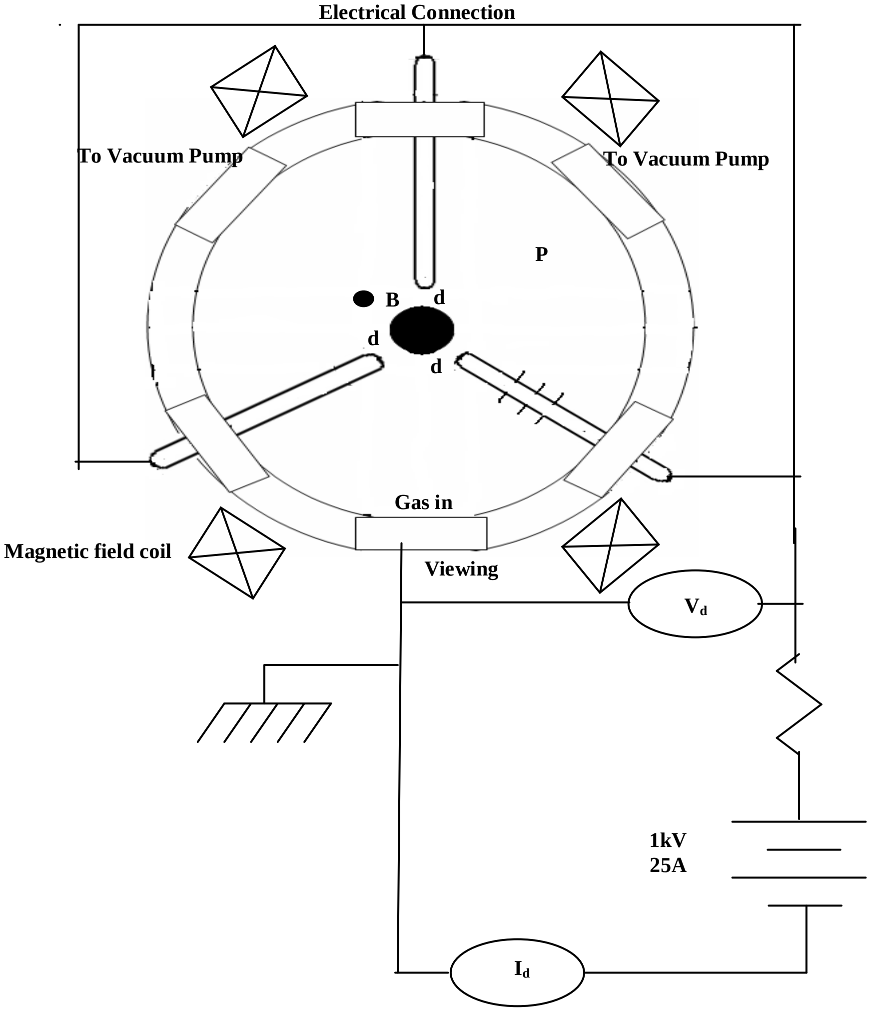

Figure 1- Schematic diagram of the experimental setup

The vacuum system consisted of a double stage rotary pump and turbomolecular pump to evacuate the chamber down to an ultimate pressure of about 10^{-5}mbar before gas feeding.

A DC-stabilized voltage was applied on the assembly supplied by a 1kV, 25A power supply so that the three electrodes were at positive potential and the chamber was at earth potential. The experimental values of the discharge current I_d and the discharge voltage V_d were recorded by a digital multimeter while a current-limiting resistance was connected in series with the power supply to avoid any short circuit current effect across the power supply. The magnetic field in which the vacuum chamber was immersed was generated by a water-cooled coil capable of delivering a field strength exceeding 0.21T at the position of the electrode tips. The magnetic field strength B was varied by adjusting the electrical current flowing through the coil turns.

The experimental run starts when the chamber was evacuated down to an ultimate pressure and then feeding the argon into the chamber, allowing the pressure to reach 100 mbar before pumping the gas out to the desired operating pressure. This process of chamber flushing was repeated three times prior to each experiment to pump out the background air and to ensure that the plasma-forming gas was pure argon. Once the desired pressure was reached, the applied voltage was gradually increased until the moment of glow discharge inception. With each applied discharge voltage, the corresponding flowing discharge current was recorded. Under a selected value of B, a range of discharge voltage values and their corresponding currents were recorded. The same procedure was followed when the electric field geometry was modified by threading one electrode with circular stainless steel discs of two different diameters. Such arrangement resulted in a reduction in the nominal electrode separation along the tapered region since the edges of these conducting discs were closer than the electrode itself to the top and bottom surfaces of the vacuum chamber. Such arrangement may also highlight the effect of current density as the existence of the discs enlarges the area of electrons collection during current flowing.

Results and Discussion

In order to establish a constructive understanding of the device bahaviour, it was necessary to envisage the dependence of the discharge voltage V_d on the product of gas pressure P and the separation d under a certain value of B.

After carrying out a number of experiments to maintain a glow discharge within the whole vacuum chamber, results demonstrated that the discharge voltage V_d decreases sharply with Pd below 4 mbar.mm under a magnetic field of 10 G (at d=20cm)as typically shown in Figure-2. Over the region of reduced pressure, i.e., on the left hand side of the V_d-Pd curve, neutral gas atoms experience limited collisional ionization and hence, less energy exchange with the electrons. Under such experimental conditions, the ionization is governed by a high (electric field/pressure) ratio, the properties of electrode material and the externally-applied magnetic field which imposes effective confinement on the charged particles [19]. At this stage, it is important to recall that very high electric field strength is required to accelerate the ionizing electrons to maintain the necessary ionization over this part of the V_d-Pd curve [22].

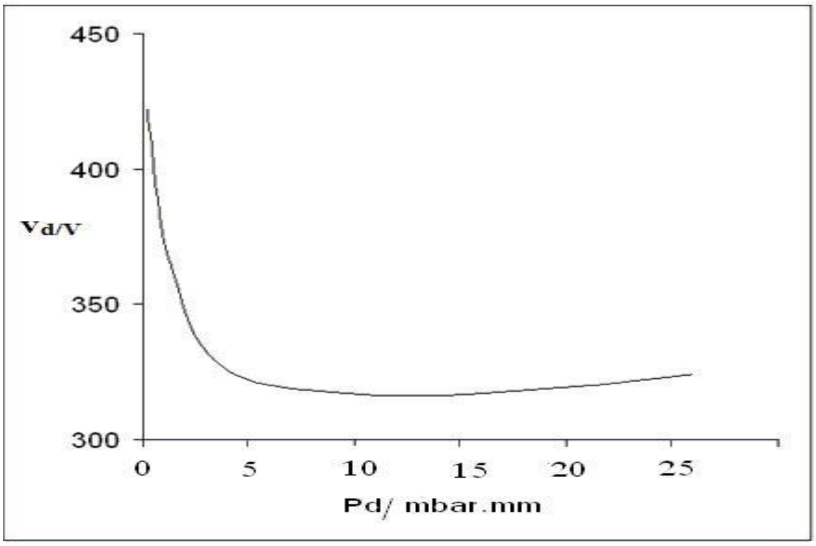

Figure 2- A typical discharge voltage-Pd curve of the experimental setup with d=200mm.

A number of characteristic parameters can be figured out in analyzing the present experiments including gas pressure P, magnetic field strength B, discharge voltage V_d, discharge current I_d, and the number and diameters of the circular conducting discs threading the electrodes for enhancing the electric field in the region between the electrodes and the internal surface of the vacuum chamber. Two disc diameters; 80mm and 140mm (3mm thick), were used and will be referred to as type (1) and type (2), respectively. The significance for having the distance (d) was to define a reference distance for how far the electrodes were inserted into the chamber before placing the discs. It is worth-mentioning that the product (Pd) here does not represent the exact sparking parameter as in other cylindrical discharge tubes and its minimum value may provide the approximate Paschen minimum value of argon in this setup. Moreover, all values of B which are referred to were measured at this electrode position d from the central column.

The direction of B is along the chamber axis which means that it is perpendicular to the electric field E in a limited region within the spacing d. Over other regions inside the chamber where the three electrodes were extended, E and B were both along the chamber axis remembering that the electrodes were having positive potential with respect to the top and bottom surfaces of the chamber which were acting as a cathode.

Over a considerable number of experiments, the cathode surface was not clean and impurities including water vapour were adsorbed onto its whole surface resulting in some observations of localized intense charged particle beams (electric arc). The values of B mentioned below were taken at the positions of the electrode tips, i.e., at d=20cm.This is relevant when the chamber is used for any experimental purposes that require higher values of B at this electrode position by increasing the current flowing in the coil. Previous experimental studies using cylindrical discharge tubes [14] have shown that the discharge voltage is sensitive to the product (gas pressure x tube radius) since the electron number density is altered within the containing volume. However, in the present setup, results of both voltage and current may be sensitive to the shortest electrode separation as well as the applied value of B which would be altered at different d.

Typical current-voltage characteristic curves were plotted from these measurements by considering specific experimental conditions and special attention was paid to the discharge steering by the variation of B, I_d, and E_d. Figure-3 demonstrates three typical characteristic curves for three values of B (10G, 200G, and 500G) when six discs of type(1) attached to each other, were threading one electrode with the first disc positioned at a distance 25cm from the electrode tip (45cm from the central column) and others followed towards the flange. With the operating argon pressure at 10^{-3} mbar and by placing the discs in this position, the value of the sparking parameter (pressure x electrode spacing) is reduced since the disc edges were nearer to the chamber surface. The lowest voltage values on the three curves represent the voltages at which the GD covers the whole chamber (Paschen minimum). Upon gradually raising V_d, the current I_d was correspondingly increased resulting in an azimuthally movement of the whole magnetized plasma towards the back electrode ends near the flanges and it was totally confined there by B at that region.

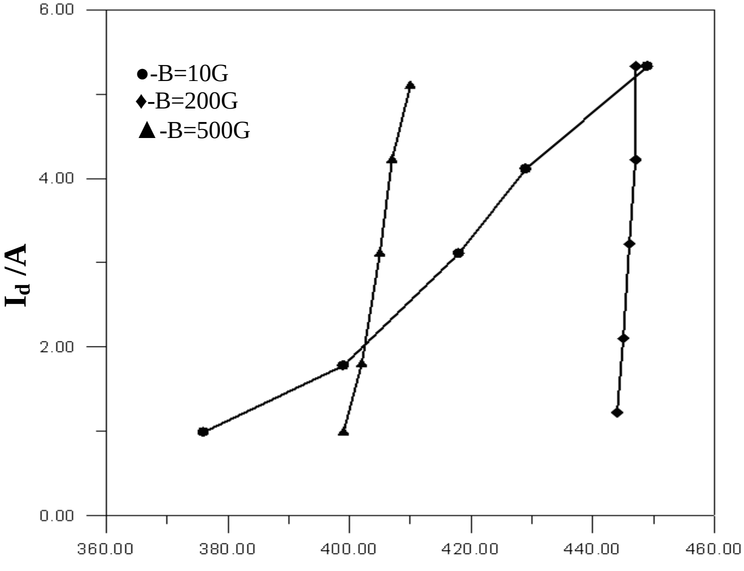

Figure 3- The dependence of the discharge current on V_d at three values of B when $P=10^{-3}$mbar, d=20cm, and 6 attached discs of type (1) threading one electrode.

A prompt increase in I_d with relatively lower values of V_d was noticeable as B was raised to 200G and then to 500G. For such arrangement and conditions, the GD appeared at lower V_d (400V) when B was set higher at 500G compared to V_d = 445V at B = 200G. The reduction of the voltage with increasing B may be due to the fact that electrons encounter more collisions with gas atoms as they spiral around the field lines leading to more ionization and consequently an increase in I_d. Increase of B sustains more electron-neutral atom collisions giving rise to more ionization and higher electron number density and a consequent increase in I_d [14]. Values of I_d, ranging from about 1A to nearly 6A, were recorded and plotted with their corresponding V_d at typical B values. Reduction of the discharge voltage with increasing B to 350G in argon was experimentally reported with plane-parallel aluminum electrodes at pressure P ranging from 0.1 mbar to 0.5 mbar [19].

In Figure-4, two I_d-V_d characteristic curves at B=500G and P=10^{-3}mbar are drawn to illustrate the effect of the diameter of the discs threading the electrode, i.e., the effective electrode separation. The first curve corresponds to the use of three separated discs of type (1), 10cm apart, while the second curve represents results when these three discs were replaced by one disc of type (2) on the same electrode (positioned at 25cm from the electrode tip). Results show that the GD appeared at a voltage of 536V with the three separated discs while it was less (336V) for the single larger disc, i.e., a reduction by a factor of almost 40% with reducing the effective electrode spacing by 30mm.

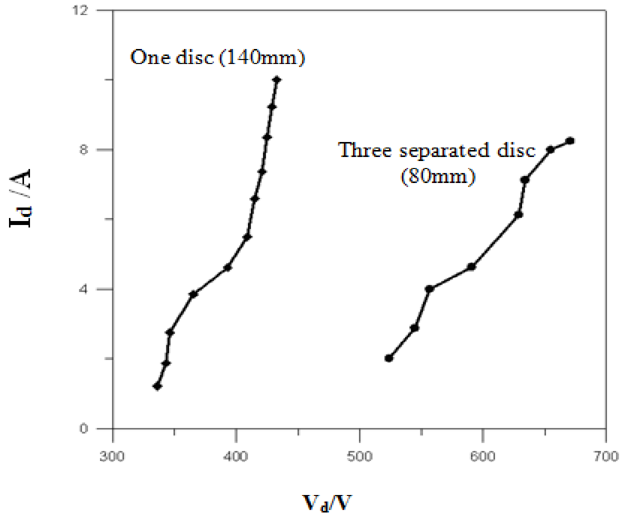

Figure 4- Comparison of typical I_d-V_d curves by using different discs at B=500G and P=10^{-3}mbar.

This result could be justified by reducing the sparking parameter as the lager disc approaches the surface of the cathode. Also, the current was found to raise four times with the three discs and was increased by more than eight times as the larger diameter disc makes less effective electrode spacing. Observations of higher current with the 140mm can be attributed to the increase of the electron velocity by enhancing the E-field in this region as the disc moves 6mm closer than the 80mm-diameter disc to the chamber surface. The drift velocity is increased as the ratio E/B is higher due to the enhancement of E. Results analysis of using 6 attached discs of type (1) at P=10^{-3}mbar and B=500G showed that I_d could be increased by nearly a factor of 5 (from 1A to 5.1A) with raising V_d, leading to a noticeable confinement of the plasma at the electrode entrance region. For the sake of comparison, these results are depicted in Figure-5 with the values recorded for one disc of type (2) replacing these 6 discs. The configuration of having 6 attached discs may have resulted in a local region of nearly uniform E-field with small spacing between the disc edges and the chamber surface. Under these circumstances, electron trajectories would be different from having a single disc which forms a region of local nonuniform E-field in which electron trajectories and particle energies are varied correspondingly. Due to the large cathode surface area of the present experimental configuration, area effect was observed when the luminous discharge area was changed as a result of varying I_d. This may justify that the current density J at the chamber surface is unchanged despite the variation of I_d in the circuit.

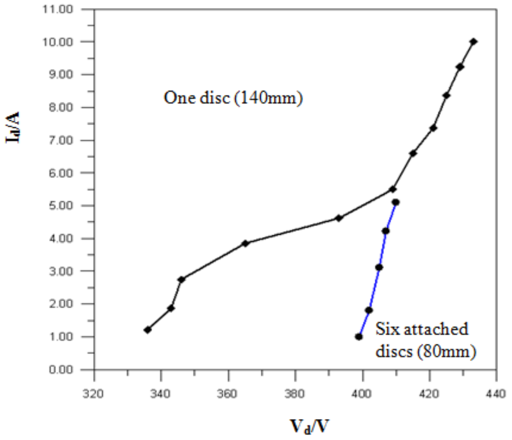

Figure 5- Typical I_d-V_d curves for different disc arrangements at B=500G and P=10^{-3}mbar.

Both Figures-4 and 5 demonstrate the effect of the electron current density (J) as these discs collect electrons with relatively larger area. The JxB effect plays a significant role in steering the discharge because of the resulting pressure gradient represented by this cross product. Such effect contributes also to the I_d-V_d curves shown here as the area of electron collection is altered by attaching or separating the discs. It was found that upon using these discs more energy was deposited to the cathode surface giving rise to an elevation of its surface temperature measured by thermocouples positioned on the outer surface of the chamber. Gradual rise in cathode temperature with I_d and time was observed with no period of instability as reported with using copper cathode. Brighter glow was observed around the disc of type (2) due to the enhancement of the electric field similar to that observed in the negative glow region [9].

Since the chamber, electrodes, and discs were made of stainless steel, it is expected that the minimum discharge voltage is lower and the sparking parameter is shifted towards a lower value in comparison with copper. Moreover, such behaviour demonstrates the effect of the ion-electron emission rate which is defined by the Townsend secondary ionization coefficient γ (rate of electron emission from the cathode as a result of ion bombardment). Such process is experienced at higher values of (E/P), i.e., in the region between the chamber surface and the disc edges where E is enhanced [19].At a background magnetic field of B=10G, the effect of P on the behaviour of the discharge was also investigated when 3 separated discs of type (1) were threading one of the electrodes. A prompt increase in I_d with V_d was recorded as P was raised by an order of magnitude (from 10^{-3}mbar to 10^{-2}mbar) due to enhanced ionization of more atoms which results in electron multiplication and subsequently higher electron number density. Under these conditions, for an increase of about 5% in V_d, the corresponding value of I_d was raised from 3A to11.7A as shown in Figure-6. The increase in the discharge currents with raising V_d accounts for extracting more electrons from unit surface area of the cathode. The ExB drift forces may be more effective on electron multiplication and $I_{d,}$ while they have weak effect on V_d along the discs region at both P values and under low B. It may be understood that the effective path of electrons becomes longer in the region where E is perpendicular to B and this may justify higher ionization as a result of higher collision rate of electrons with argon atoms. Increase of radial electron number density within the region of (d)is expected due to such drift forces as their magnitudes depend mainly upon the contribution of both electric and magnetic fields [18].

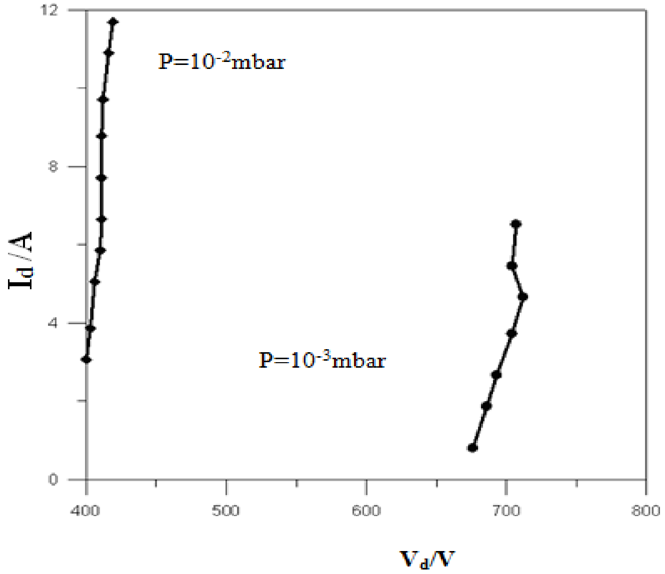

Figure 6- Typical current-voltage characteristics at two pressure values with B=10G, d=20cm, and 3 separated discs of type (1).

Because of the geometry of the magnetic field in which the chamber is immersed, the various glow discharge regions near the electrodes have been influenced throughout the confining effect of electrons. However, due to the arrangement of the setup, these individual regions are not easily identified. Careful measurements of the discharge voltage with varying magnetic field strength B may present more understanding of the discharge characteristics since this voltage determines the energy of charged particles and the flowing discharge current in the circuit.

Over a range of B of up to 525G, the discharge voltage was found to decrease with raising B until it reaches a minimum value of 330V at B=81G after which V_d starts to increase gradually with B as illustrated in Figure-7. Under these experimental conditions, such bahaviour is similar to the well-known Paschen curve of gases when the voltage shows a Paschen minimum value at a certain sparking parameter value for particular gas and cathode material.

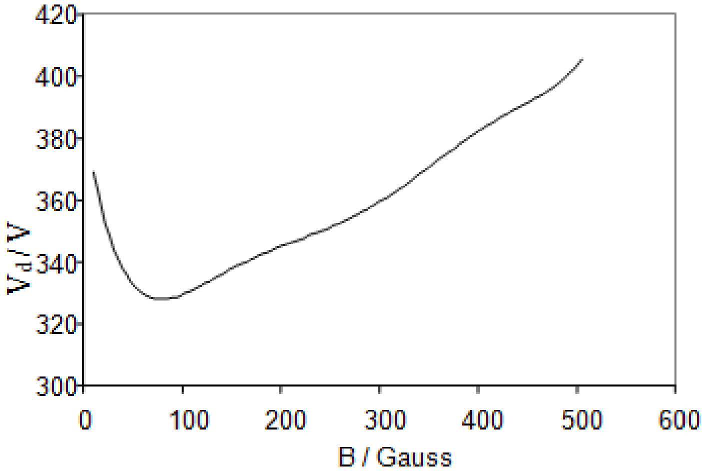

Figure 7- A typical discharge voltage-magnetic field strength curve at a gas pressure of $P=1.25x10^{-3}$ mbar.

The discharge voltage-magnetic field curve may indicate one of the characteristic effect of the B-field on the charged particle dynamics via its effect on V_d and consequently on $\frac{E_d}{P}$. It has been reported that γ rises with the B-field at certain values of reduced field $\frac{E_d}{P}$ for argon and initiating the discharge at a minimum V_d is equivalent to have a lower work function cathode surface in field free discharges [19]. According to this curve, the contribution of B to the E x B drift forces is varied with B values and also the drift velocity of charged particles are subsequently altered.

When the cathode surface was heated to a temperature exceeding 60^0C as a result of ion bombardment and flowing current, the vacuum pumping down cycle to a typical ultimate gas pressure of 10^{-3}mbar, was found to be reduced by a factor of 3 (from 6 hours to 2 hours) which demonstrates an acceptable GDC process of the internal surface of the metallic vacuum chamber under such magnetic field of strength 10G

Conclusion

Large-volume glow discharge experiments in a metallic vacuum chamber containing argon at low pressure (10^{-2}mbar and less) have shown that the current-voltage characteristics are sensitive to the geometry and dimensions of the discharge electrodes and other parameters correlated to Paschen minimum conditions. Observations have illustrated a pronounced effect of **E, B** and pressure gradient in drifting the GD plasma towards the chamber circumference to be totally confined at the entrance of the electrodes. Minimum discharge voltages were recorded with their corresponding currents ranging from 1A to more than 10A as the electric field within the electrode spacing was enhanced under magnetic field strength of up to 525G. There is a possibility that the discharge might have been operated in the normal and abnormal glow depending upon their optimum conditions. These experiments provided GDC parameters for such vacuum chamber and results may be extended to larger volume chambers, i.e., for larger surface area.

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