Arab J. Nucl. Sci. Appl, Vol 51, 2, 1-9 (2018)

Arab Journal of Nuclear Sciences and Applications

ISSN 1110-0451 | ***Web site: ajnsa.journals.ekb.eg*** | (ESNSA)

Characterization of Electrical Breakdown for Low and High Pressure Hydrogen Gas in Coaxial Virtual Cathode Device

A.M. Shagar[1], F. A. Ebrahim[1] , M. A. Abd Al-Halim[2] and M. E. Abdel-kader[1]

(1) Plasma and Nuclear Fusion Department, Nuclear Research Center, Atomic Energy Authority, Cairo, Egypt

(2) Physics Department, Faculty of Science, Banha University, Egypt

Received 9th Apr 2017
Accepted 11th Jun 2017

The DC gas discharge is established between coaxial cylindrical stainless steel electrodes. The coaxial cylindrical DC discharge device consists of an outer grid cathode and inner rods anode with 4 mm gap between them. This experimental study is focused on the effect of gas pressure and electric field strength on breakdown voltage. There is a balance between the electron attachment and first ionization collision, so the Second Townsend emission is the responsible for maintain the discharge. The I-V characteristic curves for different pressures of hydrogen gas indicate that the highest current appears for the highest gas pressure. The gas breakdown voltage varies as a product of Pd and Townsend's coefficients depends on gas pressure and E/P, where E is the electric field and P is the gas pressure.

Keywords: Paschen Curve - Townsend's Ionization Coefficients - Breakdown Voltage- A Cylindrical Coaxial DC Discharge Device

Introduction

The DC gas discharge is used in many applications such as plasma display panels, lamps, surface modification, and particle generation beside the environmental and biomedical applications [1, 2]. Much research has been carried out to provide a theoretical basis for the mechanisms of breakdown in gases.

The electrical characteristics (*I-V*) are linear for most the gas discharge. The linear form indicates that the voltage across the plasma remains nearly constant as the current increases [3]. The *I -V* characteristic also shows that the potential between the two electrodes increases with the increase of the discharge current. The discharge covers the tube outside the two electrodes, and there is an increase in applied potential *V*, which leads to an increase in the electron beam current. The breakdown voltage increases with the decrease of working gas pressure [4].

The secondary electrons emission from the cathode surface is a very effective part, where the *I-V* characteristics change accordingly [5]. The relation of the breakdown voltage as a function of the gap between the electrodes (*d*) product, a working pressure (*p*), gas composition and the gap between two electrodes as a separate parameter, i.e. $V_b = f(p \times d, d)$ has been illustrated in several researches. [6-12].This voltage is higher for cylindrical geometry than for plane one. [13] The breakdown voltages of gases are follow up Paschen's law in parallel-plate geometries, but it is not directly applicable in non-planar geometries, because of the confusion about the distance between the electrodes and distortion of the electric field.[14,15] The minimum breakdown-voltage for a cylindrical electrodes was obtained in terms of the aspect ratio *b/a*, (*a & b* are the inner and outer radii of electrodes). In a cylindrical

Corresponding author: fawziaagha7@gmail.com
DOI: 10.21608/ajnsa.2018.6505

geometry, the minimum breakdown-voltage increases from its planar value, and it is proportional to *ln (b/a)*. Departures from Paschen's law results from both non equilibrium and geometrical effects [16].

According to the "Townsend mechanism", a series of electron avalanches initiated at the cathode cause the breakdown of the gas. However, in the "streamer mechanism" a single electron avalanche can lead to a breakdown. [17-18]. with the small *pd* values the streamer breakdown mechanism is replaced by the Townsend breakdown mechanism. [19] Townsend's first ionization coefficient (α) is the number of ions produced in gas by a single electron was emitted from the cathode. The value of α was estimated in several researches [20-22]. The electron attachment coefficient η(The ionization efficiency) , which is the number of attachments produced by an electron travelling under the effect of the applied field in a unit distance. Both coefficients, α and η, are highly dependent on the applied electric field [14,23].The generated number of electrons from secondary processes per each primary avalanche γ depend on the cathode material [24,26], state of the surface [27], and the energy of ions [28,29] . The minimum breakdown voltage increases with increasing the work function of cathode materials, and also for the high value if secondary emission coefficient [30,32 ,31].

Recently, few research works has been conducted on the dc discharge on hydrogen gas compared to the studies that survey the discharge in inert gases or gas mixture. Hence, the present study is devoted to the examination of electric characteristic of hydrogen gas discharge at different pressures. The breakdown voltage and the Townsend coefficients for the coaxial cylindrical DC gas discharge device will be also investigated.

Gas breakdown and Paschen's law

Ignition voltage or breakdown voltage is the required external voltage to convert the non-self-sustaining discharge to sustaining discharge. Breakdown voltage is an important parameter of a gas discharge device. The behavior of Paschen's curve has three main stages: starting with high values of breakdown voltage, and decreased sharply to minimum value, then it rises again to high breakdown voltage. Paschen's law means that, the breakdown voltage V_b is a function of working gas pressure P and the gap between electrodes d where $V_b = f\ (pd)$. The breakdown voltage is changed according to Van Engel relation [33]:

$$V_b = \frac{C_1(pd)}{C_2+ln(pd)} \tag{1}$$

Where V_b is the breakdown voltage in Volts, p is the gas pressure in torr or mbar and d is the gap distance. The constants c_1 and c_2 are depending on the composition of the gas.

On the left hand side of the Paschen curve (before the minimum value of breakdown voltage), when the pd product is small, the electron mean free path becomes larger than the gap between the electrodes, so the electrons cannot gain enough energy to ionize the gas molecules. So a higher voltage is required for the ionization process take place and to start an avalanche.

On the right side of the Paschen curve, when the pd product is high, there are many collisions that take place through the electron travel from the cathode to the anode.[34] For most gases, the minimum breakdown voltage is between 100 and 500 volt and occurs for *Pd* in the range of 10^{-1} - 10 torr·cm [35]. The minimum breakdown voltage for noble gas increases with the increase of the work function of the cathode material and high secondary electron emission [32].

Townsend's coefficients

Paschen's law is used to describe the mechanism of gas breakdown. Townsend introduced the quantity α known as Townsend's first ionization coefficient in order to explain the current increase as a function in the voltage drop, where the average current is equal to the number of electrons traveling per second [36] will be as follows:

$$I = I_0 e^{\alpha} x \tag{2}$$

Where I_0 is the current at cathode, x is the electron traveled distance and α is the first Townsend's ionization coefficient. The first Townsend coefficient is the number of ionized ions by an electron through one centimeter distance. It heavily depends on the gas pressure, or the gas density which is a function of collision main free path, and also depends on the reduced electric field strength. The first coefficient has several forms [37].

The generalized form of α equation can be written for the planner diode as:

$$\alpha = A\text{p}\, exp(-BP/E) \quad (3)$$

Where A and B are constants depending on type of gas [38], P is the gas pressure, E is the electric field. In case of the cylindrical shape, the electric field is given by Uhn [15]: $E = V_b/(r\, ln(b/a))$ Where a and b are the inner and outer radii of the cylindrical diode and r is the distance at which the electric field is measured (r = a in our case). For the cylindrical coaxial device [39]

$$\alpha = AP\, exp((-BP)/V_b/r\, ln(b/a) \quad (4)$$

The minimum breakdown voltage in a coaxial diode has a higher value than the planar diode and it is proportional to $ln(b/a)$ [15].

Also, Townsend introduced the secondary emission coefficient which is a function of gas pressure that leads to reducing electric field strength. When the positive ions have sufficient energy to accelerate towards the cathode and impact it, new secondary electrons will be emitted from the cathode [40]. The electrons induce new ionization collision to create new ions and electrons. The second Townsend quantity known as Townsend's second emission coefficient ɣ is introduced to explain the growth of the current emitted from the cathode by the positive ions as a function in the reduced electric field strength, and the main free path collision[38].The second Townsend coefficient equation has the form[15,41]:

$$Exp \int_a^b \alpha . dr = 1 + \frac{1}{\gamma} \quad (5)$$

So, $ln(1 + 1/\gamma) = \frac{A}{B} aE(e^{-\frac{BP}{E}} - e^{-\frac{BPb}{aE}}) = \frac{A}{B} aE\left(e^{-\frac{BP(b-a)}{E}}\right)$ (6)

It is clear that the process of the secondary electrons emission at the cathode plays a great role to make a self-sustaining discharge. The ionization efficiency (η) equals to:

$$\eta = \frac{\alpha}{E} = \frac{\alpha/P}{E/P} = \frac{A}{E} P e^{-BP/E} \quad (7)$$

Experimental Setup

The experimental setup is illustrated in Fig. (1); it consists of two coaxial cylindrical electrodes closed in a cylindrical Pyrex glass tube of 10 cm diameter and 30 cm long. One of two electrodes (cathode) is stainless steel mesh installed on the inner surface of the cylindrical Pyrex glass tube, with 30 cm length, and connected to the negative voltage of DC power supply. The other electrode (anode) consists of 24 stainless steel rods each of 2 mm diameter, and 25 cm length, but the effective length is 17 cm. The rods are fixed by two flanges. The separating distance between the two electrodes is around 4 mm. Both ends of the glass tube are closed by two flanges. One of these flanges has a port covered by glass in the center, and two sealed ports for introducing the radial electric probe, and the other flange is connected to the vacuum system. Also the other flanges have three sealed ports, to gas inlet, to rod power, and to axial probe.

The device is operated using 1000 Volt stabilized dc power supply. Pure hydrogen gas is used as the working gas and its pressure (p) is varied from 0.06 to nearly 10 torr. The gas pressure measured using a dial gauge. The discharge current varies between 1mA and 100 mA.

Experimental Results

The use of hydrogen has many advantages, such as better discharge stability, easy ionization and deionization, low irritation and high load power. The hydrogen gas discharge is used to describe the flow of electric current through the hydrogen medium when a high voltage is applied between the two cylindrical coaxial electrodes at a variable pressure. Fig.(2) shows the discharge characteristics of hydrogen at pressure in the range of 1 torr up to 10 torr, and focuses on the effect of gas pressure on the applied discharge voltage, and current. It is know that the gas pressure is an essential factor in the discharge process, where the gas pressure is direct proportional to the mean free path collision. On the other hand, the applied voltage is inversely proportional to the gas densities. It is clear from Fig. (2a), that the voltage which is required to generate enough electrons to start the discharge decreases with the increasing the hydrogen pressure; at the same time, the discharge current increases. Also in Fig. (2b), the discharge voltage and discharge current reach constant values when the discharge transfers from non-self-sustain to self-sustain discharge. When a high voltage is applied between the two electrodes immersed in hydrogen medium, the electrons are emitted from the cathode, when one electron collides with a neutral particle; a positive ion and electron are formed. This process is called ionization collision.

It is shown from Fig. (3) That the $I_d - V_d$ curve, where the discharge current increases with increasing the applied voltage, also the applied voltage value changes according to the change of the pressure and inversely proportional with it. It's clear also from the curve that the discharge current takes place at normal glow region.

The breakdown voltage in a DC discharge depends on gas pressure and the inter electrodes separation. The pressure and the discharge length play an important role in the gas discharge. In this study, the pressure is the effective part for the applied voltage where the distance between the two electrodes is constant. It is clear from Paschen curve that, at right hand side, high hydrogen pressure. It is noticed that at high pressure, the ionization collision increases due to the high density and short mean free path collision, consequently, the breakdown voltage required to sustain the discharge is high.

It is shown in Fig. (4) That at low pressure, high voltage is required to generate enough electrons to start the discharge. At both extremes of the value of the pressure, the breakdown voltage required to sustain the discharge is high. The breakdown voltage reaches a minimum value of 223 Volts between the two extremes at *p.d =0.8* torr mm as shown in Fig. (4).

The first ionization coefficient α is the average number of ionizing collision made by an electron per centimeter in the field direction. α (First Townsend coefficient) is strongly dependent on the applied voltage and the anode-cathode space i.e it is a function of the electric field, ionization energy and electron mean free path where the mean free path is inversely proportional to the pressure, therefore:

$$\frac{\alpha}{P} = \phi \frac{E}{P} \qquad (8)$$

Fig. (5) shows the relation between $\frac{\alpha}{P}$ and $\frac{E}{P}$. It is clear from the curve that the number of ionization collision increases with increasing the reduced electric field, due to the consumption of the electron energy in ionization process to create the first pairs of electrons and ion. Then the curve becomes almost saturated, as a result of the balance between the ionization process and electron attachment process.

The secondary electrons emission coefficient is based on the ions accelerated by the electric field towards the cathode to release secondary electron by ion impact. This process is characterized by the secondary electrons emission coefficient [41].

$$\gamma = \frac{\text{number of electrons emitted from the cathode}}{\text{number of ions incedent on the cathode}} \qquad (9)$$

Where the number of secondary electrons which are produced per every incident positive ion is a function of gas pressure, P, and reduced electric field strength,$\frac{E}{P}$.

Fig.(6) shows the dependence of secondary electrons emission from the cathode material on the reduced electric field. It is clear that the secondary electrons emission increases with increasing of the electric field and it is responsible for self-sustaining discharge, due to the increase in the electron density which leads to increasing the ionization process. The electron attachment also plays an important role in breakdown gas and transfer the discharge from non-self-sustaining discharge to self-sustaining discharge.

The relation $\frac{\alpha}{E}$ represents the number of the negative ion produced by the electron attachment per unit potential drop or the number of electron attachment. Fig. (7) Shows the relation of the number of electron attachment (negative ion) as a function of reduced electric field. It is clear from the curve that the probability of electron attachment decreases with increasing the energetic electron which is strongly inversely proportional to gas pressure. To reach its constant value (minimum value) through increasing the reduced electric field. It is clear from Fig. (4) and Fig.(6) that there are balances between the first ionization collision and the electron attachment i.e. the second electron emission is the main factor to self-sustain the discharge.

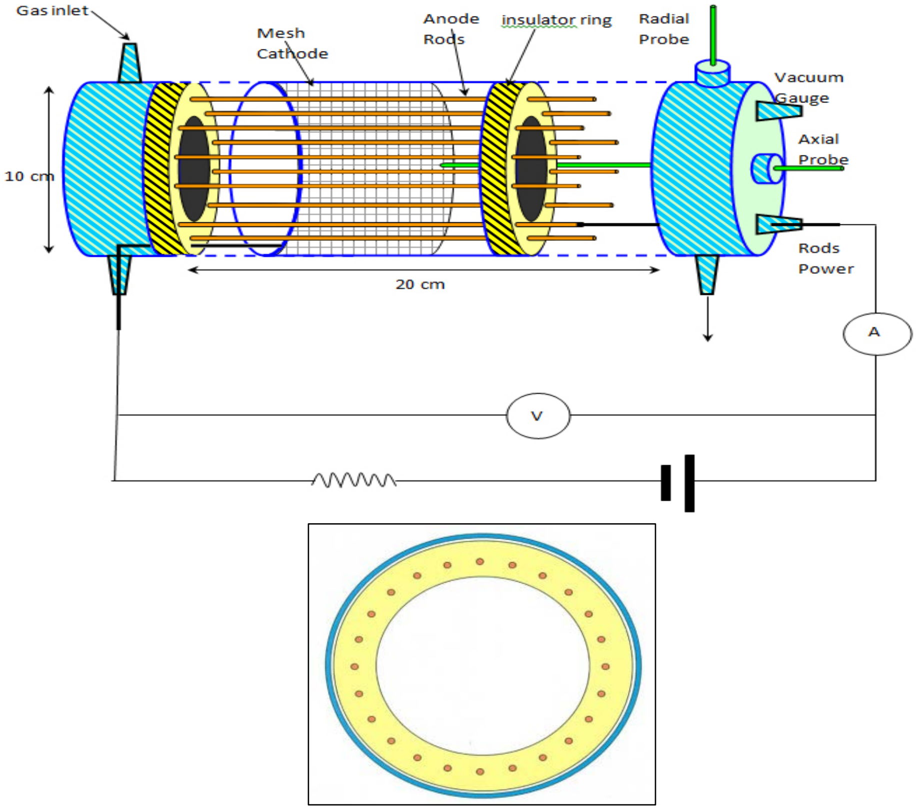
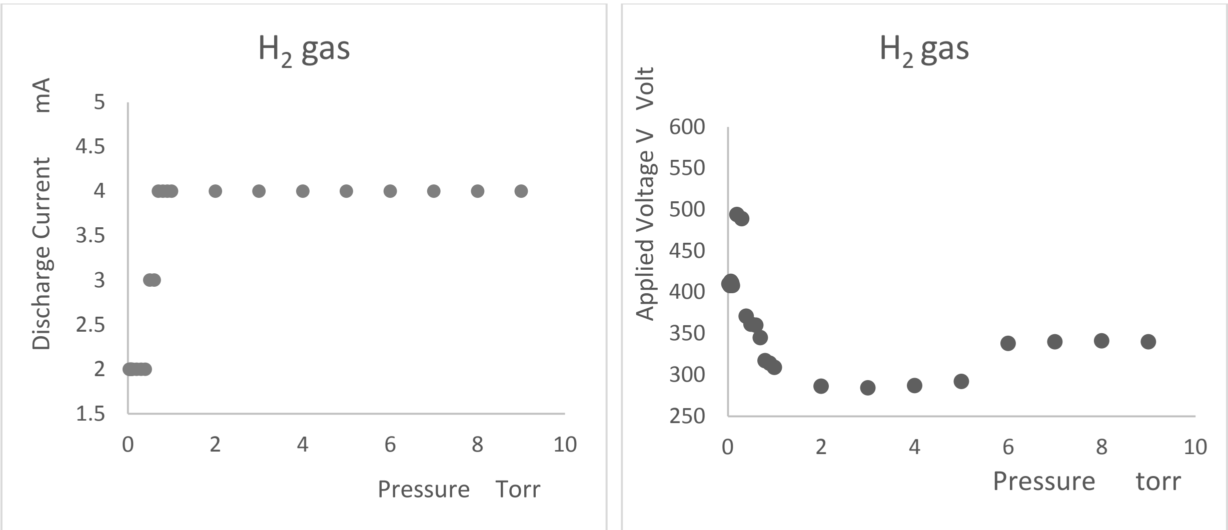


Fig. (1): Schematic diagram of the discharge chamber and its associated electrical circuit



(2a) (2b)

Fig. (2): The variation of (a) the applied voltage and (b) discharge current with the gas pressure in the range of (1 torr to 10 torr)

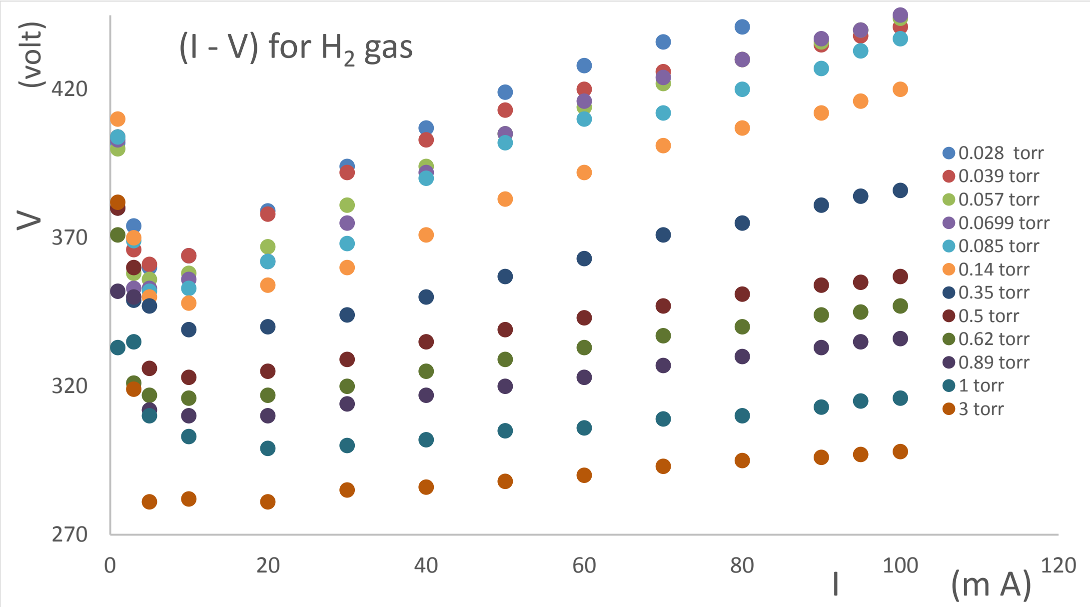


Fig. (3): The variation of the discharge current with the discharge voltage at different values of the gas pressure

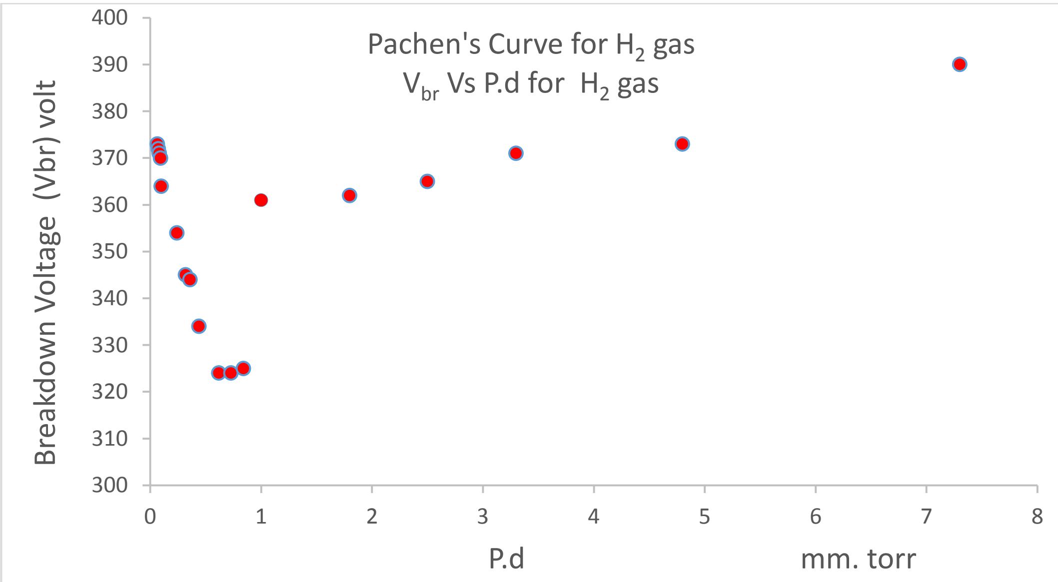


Fig. (4): The variation of breakdown voltage with the gas pressure and the distance between two electrodes (Paschen's curve)

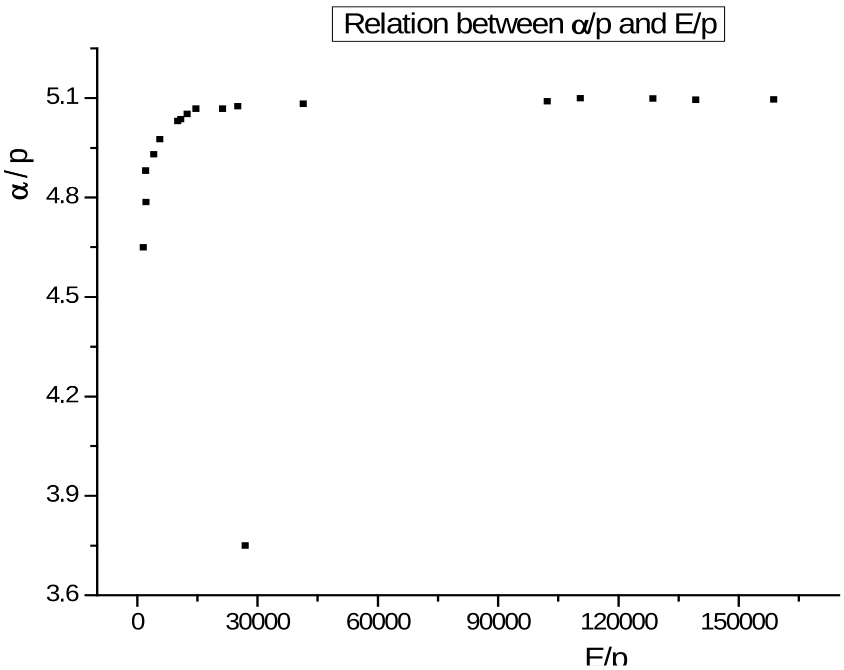


Fig. (5): The variation of the first Townsend coefficient as a function of the reduce electric field

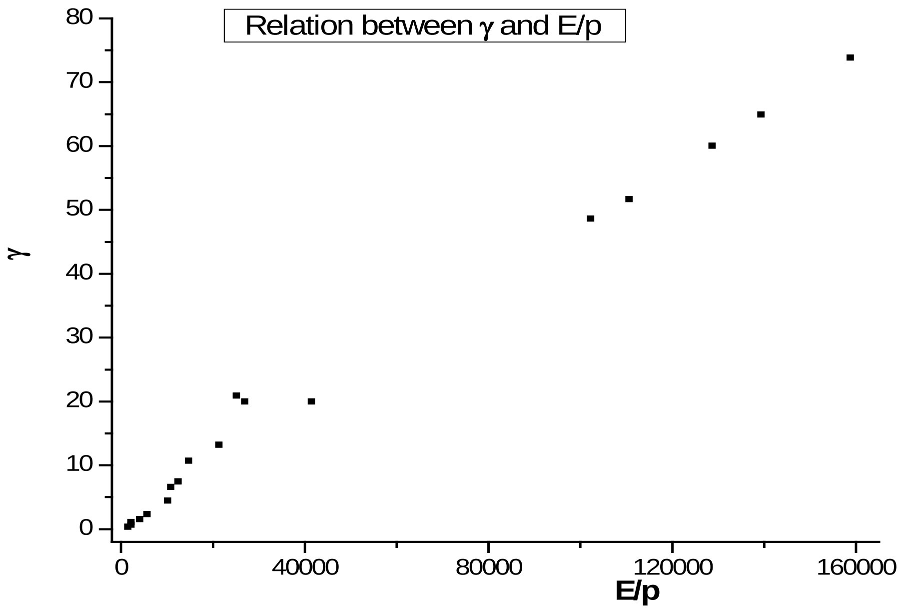


Fig. (6): The variation of the secondary Townsend coefficient with the reduced electric field

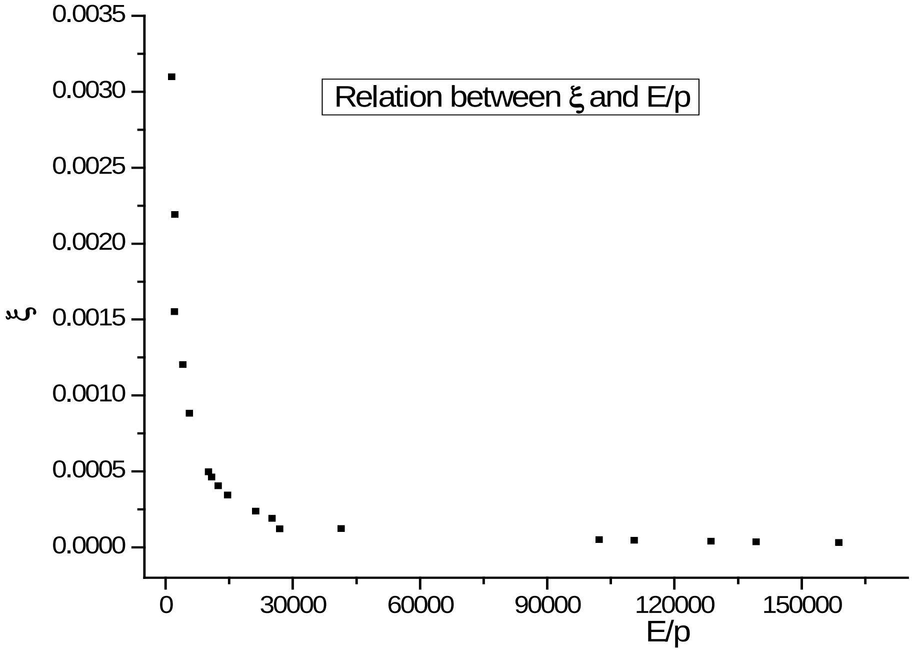


Fig. (7): The variation of the electron attachment as a function of the electric field and gas pressure

Conclusion

The breakdown is the transition of non-self-sustaining discharge into a self-sustaining discharge in Townsend regime. The pressure and electric field are important factors in Townsend discharge. The first Townsed ionization and second Townsed emission are both functions of pressure and the energy gain of charged particles between collisions. The electron attachment plays an important role where it is proportional to the first Townsend coefficient and inversely proportional to the electric field strength. Low and high pressures require a high voltage to sustain the discharge, and the minimum breakdown voltage is 223 volts at *pd= 0.8* torr .mm for the hydrogen gas.

Acknowledgment: The authors would like to thank Dr. H. A. El-Gamal and Dr H. A. Eltayeb (Plasma Physics Department, Atomic Energy Authority, Egypt for their kind support and useful discussions.

References

1- Annemie Bogaerts, Erik Neyts, Renaat Gijbels, Joost van der Mullen, Spectrochimica Acta Part B 57 609–658(2002).
2- Lisovskiy, V.A. and Y. egorenkov, Appl. Phys., D33, (2000).
3- L. F. Berzak, S. E. Dorfman and S. P. Smith "Paschen's Law in Air and Noble Gases" April 25, 2006.
4- M. A. Saudy, A. I. Eatah and M. M. Masoud, FIZIKA A 14 3, 225–232, (2005).
5- A. Bogaerts and R. Gijbels, Plasma Sources Sci. Technol. 11, 27–36, (2002).
6- Von Engel, A., 1965. Ionized Gases, 2nd edn. (Oxford Clarendon Press) (1965).
7- Atrazhev, V.M. and I.T. Takubov, Appl. Phys, D9, pp: 1735, (1976).
8- F. Paschen, Ann. Phys. 273, 69, (1889)
9- J. Townsend, Electricity in Gases (Oxford: Oxford University Press) (1915).
10- V. A. Lisovskiy S. D. Yakovin, Technical Physics 45, 727, (2000).
11- L. Ledernez, UF. Olcaytug, H. Yasuda, G. Urban, 29th ICPIG, July 12-17, Cancun, Mexico (2009).
12- T. F. Ghaleb, A. Belasri, EPJ Web of Conferences 44 (2013).
13- A. Heisen, IEEE Transactions on Plasma Science, vol.ps-4, No.2, June (1976).
14- Hoyoung Pak and Mark J. Kushner, J. Appl. Phys. 71 (l), 1 January (1992).
15- Han S. Uhm, Journal of the Korean Physical Society, Vol. 38, No. 4, pp. L295_L298, April (2001).
16- P.A.S., vol. PAS-86 no. 2, pp 200-206, (1967).
17- A. Pedersen, IEEE Trans. on P.A.S,, vol. PAS-89, no. 8, pp 2043-2048. (1970).
18- B. Loncar, R. Radosavljevic, M. Vujisic, K. Stankovic and P. Osmokrovic, Acta Physica Polonica A vol. 119 (2011).

19- Sharma, A. and Sauli, F., Nucl. Instrum. Meth. A323, 280-283, (1992).
20- Sharma, A. and Sauli, F, Nucl. Instrum. Meth. A334, 420-424, (1993).
21- The LHCb Collaboration, CERNLHCC- 2001-010, (2001)
22- Krajcar Broni´c, I. and Grosswendt, B., Journal of Applied Physics, 88, 6192-6200, (2000)
23- N. H. Malik and A. H. Qureshi, IEEE Trans. Electr. Insul, Vol EI-13 No 3, June (1978).
24- H. Jacobs and A. P. LaRocque, J. Appl. Phys. 18, pp. 199-203, (1947).
25- Baars-Hibbe, P. Sichler, C. Schrader, N. Lucas, K.-H. Gericke and S. Büttgenbach, J. Phys. D: Appl. Phys. 38, pp. 510-517, (2005).
26- F. Ghaleb, A. Belasri, EPJ Web of Conferences 44 04003,(2013).
27- A. Bogaerts and R. Gijbels, Plasma Sources Sci. Technol. 11 27–36, (2002).
28- V. Baglin, J. Bojko1, O. Gröbner, B. Henrist, Proceedings of EPAC, Vienna, Austria,(2000).
29- G. D. Kim, W. Hong, J. K. Kim, H. W. Choi and H. J. Woo, Journal of the Korean Physical Society, Vol. 42, No. 3, pp. 335338, (2003).
30- G. Malović, A. Strinić, S. Živanov, D.Marić, Z.Lj. Petrović, Plasma Sources Sci. Technol, 12 S1 (2003).
31- M. A. Lieberman and A. J. Lichtenberg ‘’Principles of Plasma Discharges and Materials Processing’’ (Wiley-Interscience),((2005).
32- F. Ghaleb, A. Belasri EPJ Web of Conferences 44 (2013).
33- A.V. Engel, ‘’Ionized Gases’’, 2nd Ed.., University Press Oxford (1965).
34- P. Carazzetti, Ph. Renaud andH. R. Shea, Proc. of SPIE Vol. 6884, 688404, (2008).
35- Alfred Grill, "Cold plasma in material fabrication" (1993).
36- M. Kanuma, "Film deposition by plasma techniques" (1991)
37- T. Aoyama, Nucl.Instr& Meth (1985).
38- Y. P. Raizer, Gas Discharge Physics (Springer-Verlag, New York, 1991)
39- Yu.I. Davydov, Joint Institute for Nuclear Research, 141980, Dubna, Russia (2006).
40- D. G. Walker, C. T. Harris, T. S. Fisher, and J. L. Davidson, Diamond Related Matls. 14,113 (2005).
41- Alaa Abu-Hashem, et al, Journal of Modern Physics, 3, 48-56, (2012).