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Influence of Axial Magnetic Field on the Electrical Breakdown and Secondary Electron Emission in Plane-Parallel Plasma Discharge

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***Abstract*—**The influence of axial magnetic field (B=0.48 T) on the variation of ionization efficiency coefficient η and secondary electron emission coefficient γ with respect to reduced electric field E/P is studied at a new range of plane-parallel electrode spacing (0< d< 20 cm) and different nitrogen working pressure between 0.5-20 Pa. The axial magnetic field is produced from an inductive copper coil of radius 5.6 cm. The experimental data of breakdown voltage is adopted to estimate the mean Paschen curves at different working features. The secondary electron emission coefficient is calculated from the mean Paschen curve and used to determine the minimum breakdown voltage. A reduction of discharge voltage of about 25% is investigated by the applied of axial magnetic field. At high inter-electrode spacing, the effect of axial magnetic field becomes more significant for the obtained values of η but it was less for the values of γ.

***Keywords*—**Paschen curve, Townsend coefficient, Secondary electron emission, Magnetic field, Minimum breakdown voltage.

I. INTRODUCTION

FOR the purpose of exploring the better understanding of the complex mechanisms of gas discharge, the characteristics of electrical breakdown of several gases under the effect of applied magnetic field have been subjected in many researches. These researches included the study of magnetizes plasma discharge at different working parameters such as the pumping gases, the materials and the geometry of electrodes, gas pressure, chamber temperature, humidity of discharge chamber and the type of applied voltage [1]-[4]. Tan et al [3] investigated a new method of measuring the secondary electrons emission by two Faraday cups with and without presence of a magnetic field. One Faraday cup detects the electrons emerging perpendicularly to the target surface and magnetic field lines, while another cup detects electrons flowing along the field lines. The electrical breakdown is presented by Petraconi et al [2] at low-pressure of argon and nitrogen gases under the influence of an external longitudinal magnetic field. Plane-parallel aluminum electrodes is used at various spacing (4cm < d < 11cm) with a dc voltage (0<V< 1 kV). A measurement of the secondary electron-emission coefficient γ from MgO film in a plasma display panel is carried out by Uhm et al [5]. The influence of the secondary electron emission on the breakdown voltage in micro discharges on the plasma display panel is investigated by making use of the Townsend sparking criterion. Auday et al [6] presented an experimental study of the effective secondary emission coefficient for rare gases and copper electrodes. The measurements are made for variations of the effective secondary emission coefficient with reduced field E/p at different parallel plane electrodes spacing (2mm < d < 1cm).

In the present work, the influence of the magnetic field on the characteristics of electrical breakdown and on the properties of Townsend discharge is motivated as an important mechanism for measuring the Paschen curves, ionization efficiency coefficients η, secondary electrons emission γ and the minimum breakdown voltages V_m with and without applying an axial magnetic field. This study contributes Townsend discharge regime at a new range of plane-parallel electrode separations (0<d<20cm) and different working pressure.

II. THEORY OF ELECTRICAL BREAKDOWN

The multiplication of gases is referred to the ionization process by a collision under the field of electrical potential. The first Townsend coefficient α of the gas is denoted as the number of electron-ion pairs created by a single electron drifting per unit distance in the field direction in a gas. It depends principally upon the nature of the gas, the gas pressure, and the electric field intensity. In a constant parallel electric field region, the gain is an exponential function of the distance traveled by the electrons and the first Townsend coefficient of the gas. Thus, the first Townsend coefficient can be obtained as a function of the reduced electric field intensity E/P as follows [7]:

$$\alpha(E/P) = C_A P \exp(-\frac{C_B}{E/P}) \qquad (1)$$

where E is the electric field in units of V/cm, and P is the gas pressure in units of Pascal. The constants CA and CB are uniquely determined from the experimental data for each gas species and found to be roughly constant over a range of voltages and pressures for any given gas. For the nitrogen gas at room temperature and humidity 53%, the value of CA and

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CB are 10.95 $Pa^{-1}m^{-1}$ and 273.75 V Pa^{-1} m^{-1} respectively [8]. The coefficient α is related to the ionization rate νi which is equal to the number of ionization events caused by an electron in a unit time [2]:

$$\nu_i = n\int_{\varepsilon_i}^{\infty} f(\varepsilon)q_i(\varepsilon)\sqrt{2e/m}\sqrt{\varepsilon}d\varepsilon \tag{2}$$

Here εi is the ionization energy of the atom, f (ε) is the electron energy distribution, and qi(ε) is the cross section for ionization of an atom from the ground state in collision with an electron of energy ε. Since α is equal to the number of ionization events per unit path length, obviously:

$$\alpha = \nu_i / \nu_d \tag{3}$$

where vd is the electrons drift velocity. It is more convenient to use the ionization coefficient η (or ionization efficiency) which is defined as the number of ionization events caused by an electron that passed through a potential difference of one volt:

$$\eta = \frac{\alpha}{E} = \frac{\nu_i}{\nu_d E} \tag{4}$$

This quantity depends only on the reduced electric field E/P. One of the important parameters in this study is the effective secondary electron emission coefficient γ or the second Townsend coefficient. It represents the number of secondary electrons detached from the cathode by various particles produced in the gas (positive ions, photons, excited atoms...) and is dependent on what the electrode is made of and the type of filling gas used. Its value is related to Townsend's first ionization coefficient α by the formula [6]:

$$1 + \frac{1}{\gamma} = \exp(\alpha d) \tag{5}$$

where d is separated distance between the electrodes. The above formula can be written as:

$$\gamma = \frac{1}{\exp(\frac{\alpha}{P} \times Pd) - 1} \tag{6}$$

The values of α/p as a function of the reduced electric field E/P are calculated by knowing E/P=Vb /Pd from the determination of Vb (breakdown voltage). The values of □/p are then introduced into Eq. (6) giving γ. The discharge voltage is a function of Pd, which is a product of gas pressure P and anode-cathode distance d. the minimum breakdown voltage [5]:

$$V_b = V_m = C_B Pd \tag{7}$$

occurs at the parameter:

$$Pd = \frac{2.72}{C_A}\ln(1 + \frac{1}{\gamma}) \tag{8}$$

Thus Eq. (7) is simplified to:

$$V_m = 2.72\frac{C_B}{C_A}\ln(1 + \frac{1}{\gamma}) \tag{9}$$

The constant C_B in Eq. (9) is proportional to the electron-ionization energy of the gas species, while the constant C_A is related to the ionization cross section of the gas species. The larger the ionization cross section, the larger the value of the constant C_A. Thus, the discharge voltage in Eq. (9) can be considerably reduced for the gas species with a large ionization cross section. Remember that the secondary electron-emission coefficient γ is typically much less than unity for most gas species. Therefore, Eq. (9) shows that the discharge voltage decreases significantly as γ increases.

III. EXPERIMENTAL SETUP

The experimental setup, figure 1, consists of a cylindrical discharge chamber, simple induction coil made of copper with constant radius 5.6 cm and placed around the discharge chamber and a high voltage power supply (HVP) with electrical meters diagnostics. The discharge chamber is 50 cm long and 5.3 cm diameter and made of Pyrex glass tube fitted with a 3.2 cm fixed planer circular electrode at each side (Parallel-Plane electrodes). The discharge tube has one gas in port and one gas out port. The electrodes are made of stainless steel material. The parallel electrodes are fitted to withstand up to twenty Pascal pressures inside the discharge tube. The electrodes are positioned exactly in the center of discharge tube and are directed toward each other.

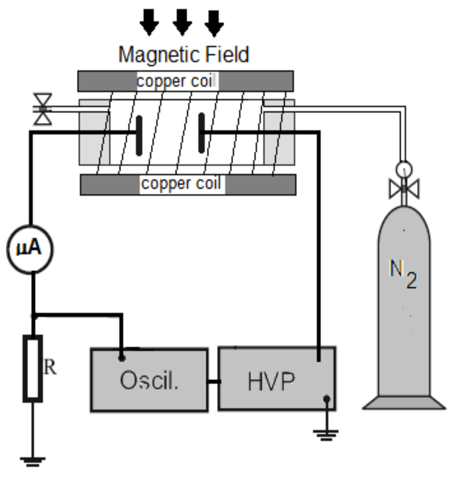

Fig. 1 Schematic diagram of the experimental setup

The magnetic circuit is made of an induction copper coil. The determination of the coil radius is restricted by the creation of sufficient magnetic induction in the discharge chamber. This demands that the diameter of the induction coil must coincide with the outer diameter of the discharge tube. The magnetic flux density near the discharge electrode could be changed by increasing the pass current through the induction coil. The measurement of the magnetic field distribution is performed using a Hall's probe and Leybold 51662 Teslameter.

The mean discharge current is determined as the mean value of the signal obtained from the voltage drop on the earthed resistor R. The current signal is recorded on the first channel of digital storage oscilloscope (5510 Hung Chang 100 MHz). The breakdown voltage is determined as the mean value of the signal recorded on the second channel of this oscilloscope through the high voltage meter (Kv). The experimental measurements at different inter-electrode spacing, different working pressure and various magnetic flux density are recorded at room temperature (T=24-27°C) and humidity of about (50-55 %).

IV. RESULTS AND DISCUSSION

1. Breakdown Voltage and Paschen Curves

The measurement of breakdown voltage of the nitrogen plasma discharge is acquired at pressure range of 0.5 Pa to 20 Pa and an inter-electrode spacing of 5, 10, 15 and 20 cm. The confinement of electrons rather than ions is performed at magnetic field intensity of 0.48 T. The Paschen curve relates the breakdown voltage over a gap as function of the pressure P and the length of the gap d. Fig. 2 shows the mean Paschen curves for nitrogen plasma discharge at different inter electrode spacing with and without applying the axial magnetic field. These curves are related to the electric field that is the voltage over the gap; Thus Paschen curves are plane-parallel gap-dependent as indicated by two coefficients (C_A and C_B) as in Eq. 1[7]. The breakdown is occurred when a sufficient number of collisions are existed to perform a required ionization in the gap vacancy. The most important advance of applying the axial magnetic field on the plasma discharge systems is concerned with that the electron free paths across the gas chamber is lengthened and the lateral diffusion of the electrons is reduced. This implies that the losses of electron are decreased and the number of collisions with the gas molecules is increased. Accordingly, the breakdown voltage is reduced as shown in Fig. 2.

In this work, a significant downward of Paschen curves is observed under the influence of axial magnetic field especially in the region of Paschen's minimum because of the higher efficiency of the secondary ionization processes in nitrogen plasma discharge. The experimental results showed a fast decreasing of the breakdown voltages on the left side of the minimum Paschen curves and gradually increasing on the right side as Pd is increased. This can be attributed to the increase of collision frequency on the left side and decreasing the ionization cross section on the right side for which more energy is required for electrons to reach the breakdown voltage [2].

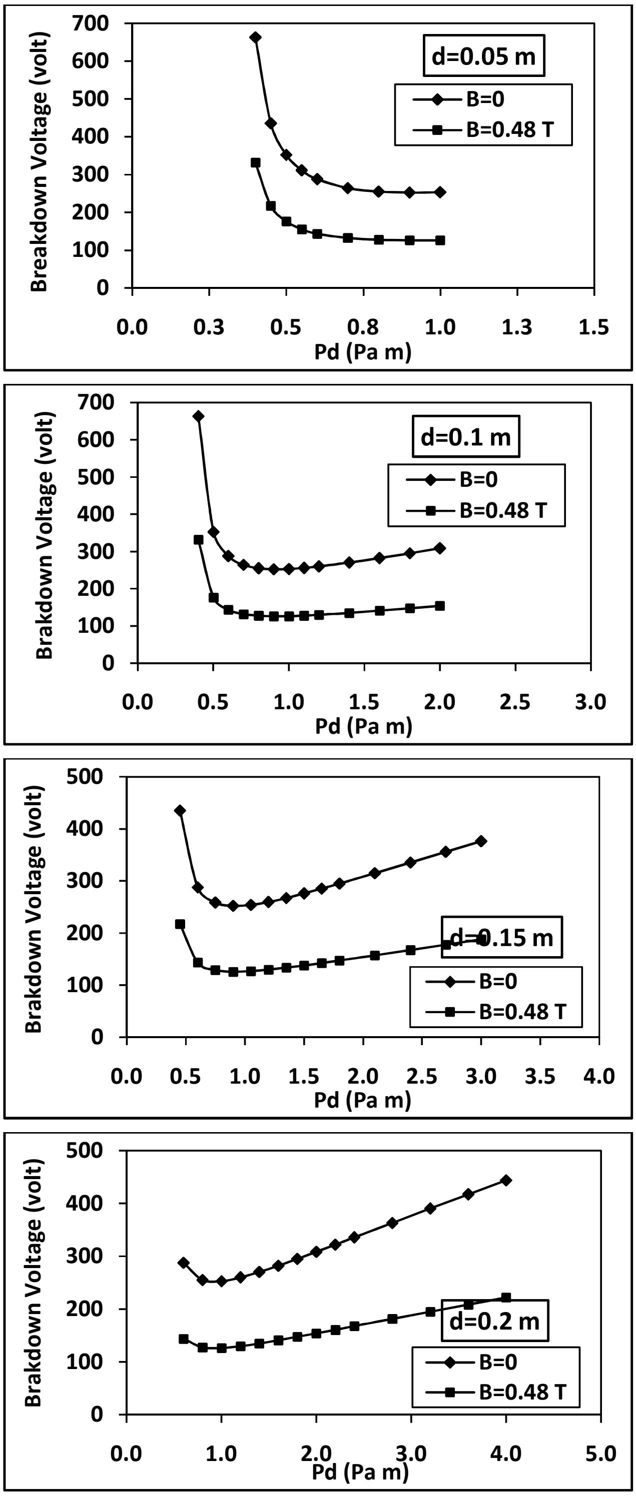

Fig. 2 Paschen curves for nitrogen plasma discharge at different inter-electrode spacing with and without applying the axial magnetic field intensity.

2. Variation of η with E/P

The influence of axial magnetic field on the variation of ionization efficiency coefficient η with reduced electric field is shown in fig. 3. At high inter-electrode spacing and low working pressure, the effect of axial magnetic field becomes more significant on the behavior of η versus E/P. As the inter-electrode spacing increases at low working pressure; the number of collision between the released electrons with the nitrogen molecules is decreased thus the confinement of electrons by the magnetic field is enhanced the values of η as the reduced electric field is decreased.

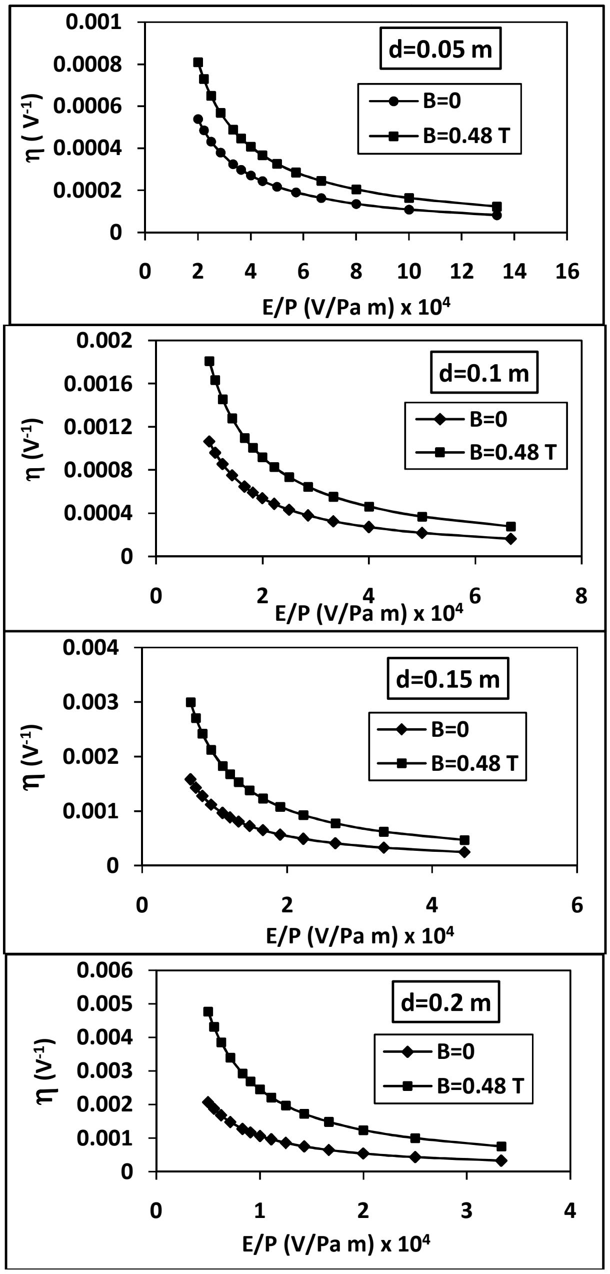

Fig. 3 The variation of ionization efficiency coefficient η versus E/P at different inter-electrode spacing with and without applying the axial magnetic field.

The literature showed that η versus E/P has a maximum value of $\eta_{max} = C_A C_B^{-1} e^{-1}$ [2].The maximum value of η that reached in this study was 0.0025 v^{-1} while the actual value is η_{max}=0.014 v^{-1}, therefore only the descending branch of η is obtained. In the absence of magnetic field, the required voltage for maintaining the breakdown discharge depends on the work function of cathode material for which a high voltage should be supplied if the cathode is made of high material work function. The present of magnetic field lengthens the trajectory of free electrons (i.e. Larmor frequency) in ionization region and decreased the mean energy of released electrons to reach anode which in turn increases the number of collisions [1].

3. Variation of γ with E/P

The values of secondary electron emission coefficients γ are calculated from the mean Paschen curves and represented in fig. 4. It is reported that the curves of γ versus E/P has a minimum value of γ for several gases such as Ne, Ar, Kr and Xe [6]. In this work, only the ascending branch is investigated. At small inter-electrode spacing and high reduced electric field, the confinement of released electrons is enhanced by the axial magnetic field. Therefore, the associated effect of magnetic field increases the values of γ as the reduced electric field is increased.

For high values of E/P, γ rises more strongly in the present work than in the literature. This could arise from the excitation within the gas becomes greater than ionization as indicated by the low values of the ionization efficiency coefficient η. For small value of E/P, the electrons are released from the cathode by a resonant photons emission (photoelectric effect). As d increases, this process loses importance since any photon emitted has less chance of striking the cathode. Therefore, for low fields the coefficient γ also depends on the value chosen for d [9].

4. Variation of V_m with γ

The discharge plasma is generated by the electrical breakdown. Reduction of the discharge voltage is therefore the key element in enhancing the electrical efficiency for plasma generation. An enhancement of the electrical efficiency of plasma generation also prolongs the system's lifetime, eliminating unnecessary heat and stress generation in the system. There is a collection of previous work on reducing the discharge voltage in uniform electric field. The reduction of discharge plasma is proportional to the parameter C_B/C_A for which the behavior of Paschen curves plays an important role in determining the minimum breakdown voltage [10].

In the present work, the reduction of discharge voltage is enhanced by applying the axial magnetic field to the discharge chamber. The calculated values of γ from the mean Paschen curves with and without axial magnetic field are used to determine the values of minimum breakdown voltage V_m using Eq. 9. Fig. 5 shows plots of the V_m versus the secondary electron emission coefficient in absence and present of magnetic field. The constants C_A and C_B for the nitrogen gas are known, therefore, the solid curve has been the least square fitted to the experimental data by which the parameter C_B/C_A=86.

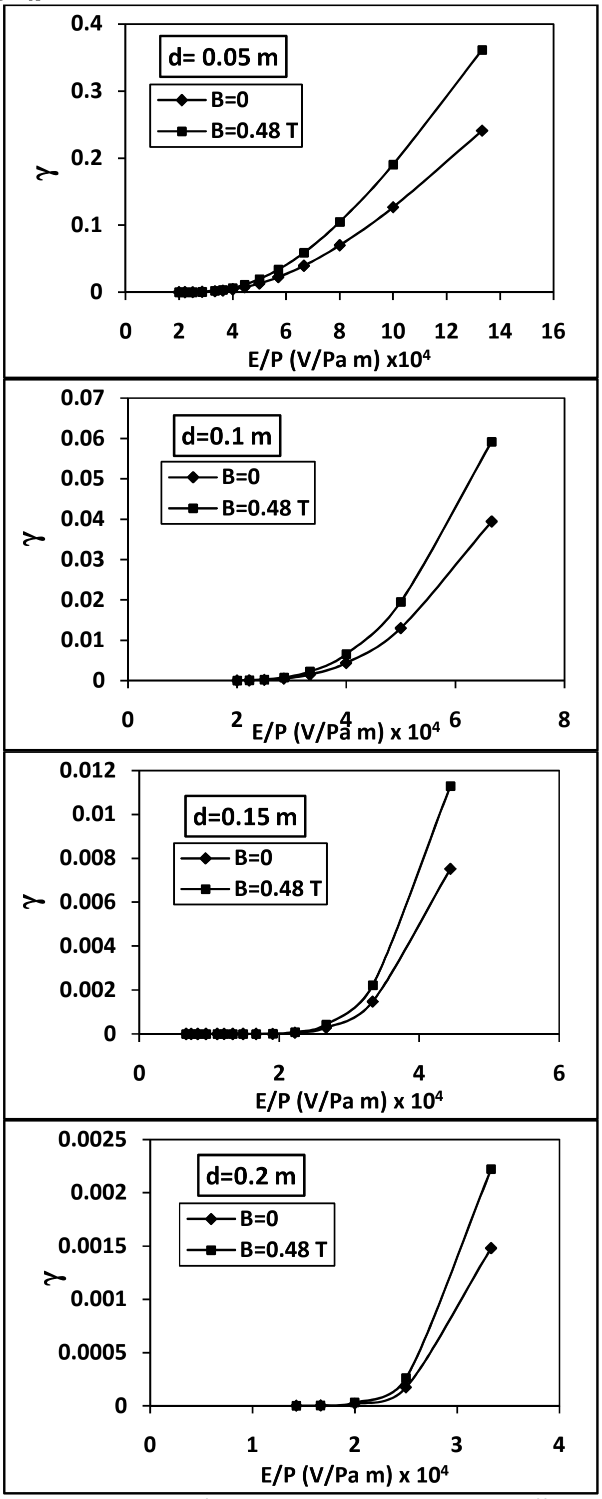

Fig. 4 The variation of secondary electron emission coefficient γ versus E/P at different inter-electrode spacing with and without applying the axial magnetic field.

As shown in fig. In the present of axial magnetic field, the minimum breakdown voltage decreases about 25% when the secondary electron-emission coefficient increases at fixed inter-electrode spacing. A minimum reduction of discharge voltage is observed at d=0.05 m because of high generation of secondary electrons. As d increases, the coefficient of secondary electron emission is decreased and therefore the effect of magnetic field becomes more significant to reduce the discharge voltage.

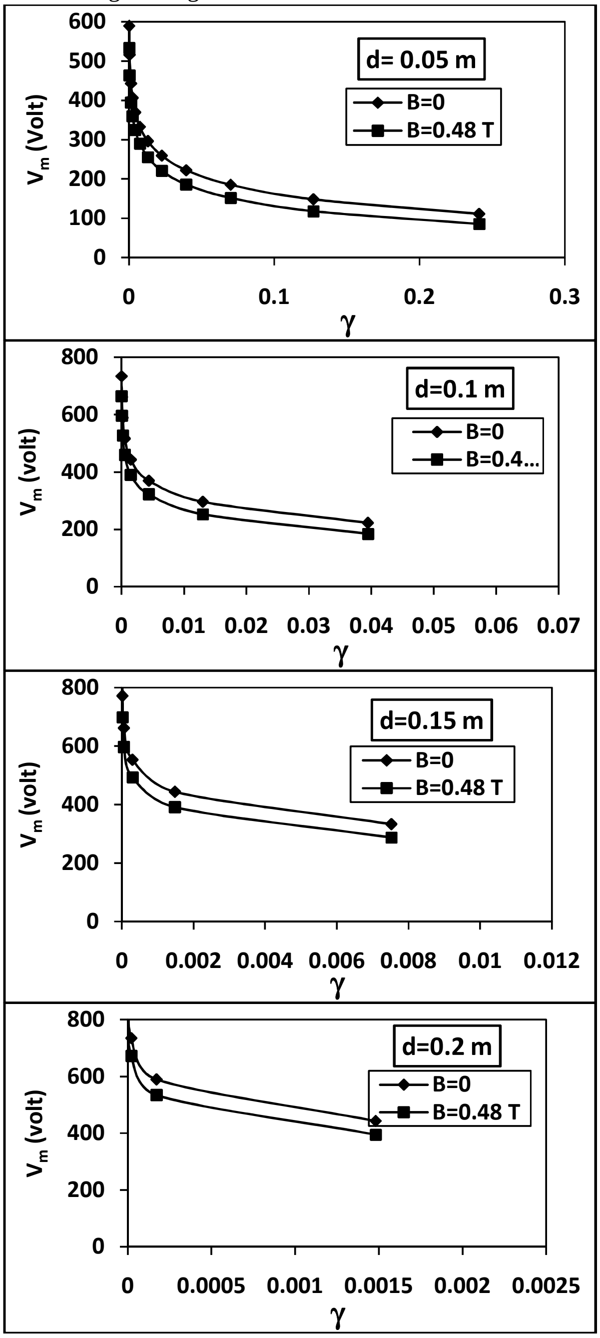

Fig. 5 The variation of minimum breakdown voltage V_m versus γ at different inter-electrode spacing with and without applying the axial magnetic field.

V. Conclusion

In the present paper, the experimental results of the electrical breakdown and secondary electron emission coefficient under the influence of axial magnetic field are compared with the literature of previous works and showed a good agreement. The most important conclusions are:

1. The influence of axial magnetic field causes a significant downward of Paschen curves in the region of Paschen's minimum in form of a fast decreasing of the breakdown voltages on the left side of the minima and gradually increasing on the right side.
2. At high inter-electrode spacing and weak reduced electric field, the variation of η versus E/P becomes more importance under the confinement of axial magnetic field.
3. At small inter-electrode spacing and high reduced electric field, the associated effect of axial magnetic field increases the values of γ as the reduced electric field is increased.
4. The discharge voltage is reduced by 25% with axial magnetic field as the secondary electron-emission coefficient increases at fixed inter-electrode spacing. The minimum discharge voltage is observed at d=0.05 m because of high generation of secondary electrons.

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