The magnetized plasma effect on cathode fall thickness for helium gas discharge

Our previous study showed that the thickness of the cathode fall region in magnetized DC argon plasma was about 3.3 mm has been investigated using two different methods, namely: the axial potential distribution and the current density distribution along the glow discharge regions. The present study demonstrates the same measurements but carried out for Helium gas discharge at the edge and center of the cathode surface for the same characteristic of the DC (cold cathode) magnetron sputtering unit . The I_a–V_a characteristic curves of the glow discharge and the axial potential distribution and the current density distribution have been investigated. Under the influence of magnetic field, the thickness of the cathode fall region for He discharge is about 2.5 mm for the two methods in pressure (P) range of 1–4 mbar. Apparently for helium gas discharge, a reduction of the cathode fall thickness (about 20%) has been found in the presence of a magnetic field at the center of the cathode and (about 37%) at the edge, furthermore stronger electric field at the edge of the cathode fall, and hence high rates of sputtering are expected.

Keyword: DC glow discharge; cathode fall thickness; Helium gas discharge; magnetic field

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1- INTRODUCTION

Low-temperature plasma generators are extensively used in different branches of industry, and the technological processes developed on their basis have been long applied at many project. One of the possible ways of raising energy and efficiency of plasma technologies is the use of magnetic field.
Recently, the performance of plasma in magnetic field has been improved in many non-equilibrium glow discharge plasma, used in dispensation of semiconductor materials for many processes such as etching and coating, because the application of a magnetic field results in enhancement of some attractive features of specific plasma sources [1].

Experimental and theoretical studies of the electric field distribution in the cathode-fall (CF) region of an obstructed abnormal glow discharge in hydrogen were discussed [2]. It is shown that the cathode temperature influences significantly the main parameters (electric field distribution, thickness of the cathode fall layer, current density, gas temperature) of the cathode fall of the self-sustained normal DC atmospheric pressure glow discharge [3].In the early days, people focus on the plasma free of the magnetic field; in the later days, many studies have been done on plasma in a magnetic field, but most of them were about common laboratory plasma, i.e., in which the magnetic field is not strong enough to make an ion do a cyclotron motion in the sheath before it strikes the wall [4].

The magnetic field parallel to the axis of the positive column of a discharge is used by Von Engel [5] known to impart a rotary component on the radial motion of electrons. This reduces the flow of both positive ions and electrons to the wall, causing a corresponding decrease in the radial and longitudinal components of the electric field and in the electron temperature.

In the present work, we report on study the cathode fall thickness under the influence of the magnetic field by two different method for He gas discharge, the axial potential distribution method and the current density distribution method.

2- EXPERIMENTAL SETUP

More details about the system, the magnetized DC plasma circuit and the plasma cell has been discussed previously elsewhere and discussed briefly in our previous work [6]. The DC plasma system consists of a stainless steel chamber that has few glass ports, connected to vacuum system and evacuated to 10^{-4} Torr. The used gases were then admitted to the system via needle valves.

Two hollow permanent circular magnets are placed around the cathode surface to produce the magnetic field, with radial diameter 80 mm and a hollow at the center of the magnet for the cathode position with the same diameter 50 mm . The geometry and the dimension of the magnet is shown in figure (1.a,b), where figure (1.a) shows the schematic diagram of the plasma cell and different region of plasma especially our interested region cathode fall, and figure (1.b) shows the radial and axial distribution for the magnetic field strengths as measured by MG-4D Hall probe, which is a fully portable hand-held Hall effect gauss meter.

As shown in the previous study a single cylindrical Langmuir probe is immersed inside the glow discharge plasma. the single probe 1.0-mm diameter and length 0.5 mm, molypedum wire is used to measure the axial potential distribution of the discharge.

3- RESULTS AND DISCUSSION

3.1 Distribution of the magnetic field strengths

In our previous study, we discussed briefly axial and radial distribution of the magnetic field B , where it was observed that B is maximum at the two cathode edges and minimum at its center (the center of the hollow magnets also).moreover B is maximum at the cathode fall region then it decreased toward the anode passing through the negative glow and positive column regions.

3.2 The different characteristics of the magnetized DC-glow discharge

3.2.1 breakdown potentials

Figure (2) shows the (I_a-V_a) characteristic curves of the helium gas discharge in the pressure range of (0.53 - 4.0) mbar, whereas the distance between the two electrodes was fixed at (3 cm). This distance is long enough for the existence of the different regions of the glow discharge [7]. The upper limits of I_a and V_a are limited by the power of the DC power supply. Since at low pressure, the probability of electron ionizing collisions with atoms will decrease (i.e. the mean free path will increase) large values of the discharge voltage will be required to maintain the discharge and a small discharge current I_a is expected. At high pressures number of electron-atom ionizing collisions increases. Thus, more electrons and positive ions are produced and consequently, the discharge current is increased at the same voltage [8].

On the other hand, the (I_a-V_a) characteristic curves of Helium gas at pressures of (0.53, 1 2, 3, and 4 mbar) when the external magnetic field is applied are shown in Fig (3). The curves are similar to those without magnetic field.

Figures(2,3) show that the breakdown potentials (V_B) of the discharge are lower when the magnetic field is applied, this can be explained as follows: the current density can be increased by the magnetic field ,due to the effective increase in the gas pressure . This is related to the fact that the presence of the magnetic field increases the apparent gas pressure and thus decreasing the mean free path, hence more excitation and ionization processes occurred and consequently the breakdown potential decreased .

The decrease of the discharge voltage in the magnetic field results from the increase in the number of collisions between the primary electrons and neutral gas atoms. The effects of the magnetic field are qualitatively considered to be effective pressure P_e , given by [9].

$$\frac{P}{P_e} = [1 + (\omega t)]^{1/2} \qquad (1)$$

Where ω is the cyclotron frequency of the electron and τ is the mean free time of the electron. since [10]

$$\omega = \frac{eB}{m} \qquad (2)$$

and

$$\tau = \frac{\lambda_0}{P[2\left(\frac{e}{m}\right)V_0^{1/2}]} \qquad (3)$$

then

$$\omega\tau = \frac{B\lambda_0(\frac{e}{m})^{1/2}}{\sqrt{2}\, PV_0^{1/2}} \qquad (4)$$

Where λ_o is the mean free path of the electron at 1 Torr, B is the strength of the magnetic field, (e/m) is the specific charge of the electron and Vo is the acceleration voltage for the electron. Taking B = 100 Gauss , P = 1 Torr (He), V_o = 100 Volt and λ_o = 0.05 cm, we obtain ωτ = 5×10^3, and P_e = 0.05 Torr. Values of the discharge current in the presence of the magnetic field for helium are smaller to those in the absence of the magnetic field. Thus, slopes of the (I_a-V_a) curves in the presence of the magnetic field are smaller than those in the absence of magnetic field, (i.e. the resistance of the discharge is larger when no magnetic field is applied).

3.2.2 Cathode fall thickness

The cathode fall thickness can be determined by two methods :

3.2.2 –a The axial Potential Distribution over the cathode fall thickness

The axial potential distribution has been measured along the axis of the discharge tube using single probe; at different gases pressure for He gas shown in Figs. (4,5,6,7) measurements in the absence and in the presence of the magnetic field, at the edge and at the center of the cathode .
Figures (4,5,6,7) show that, the potential increases rapidly axially near the cathode until it reaches a maximum value at the end of cathode fall region, this rapid increase

in potential can be referred to the existence of positive space charge within the cathode fall region. After the peak, the potential decreases less rabidly due to the existence of the reversal field in the negative glow and at the beginning of Faraday dark space (FDS) [11].

On the other hand, Fig.(8) shows the cathode fall thickness (d_c) at the edge measurements, in the presence and in the absence of the magnetic field, at different He gas pressure. It can be seen that (d_c) decreases with increasing in the gas pressure. The decreases in d_c as the gas pressure increases can be attributed to the increase in the ionizing collision frequency and hence the discharge needs less distance to create the negative glow region. Also Fig.(9) show that the thickness of the cathode fall, in the presence and in the absence of the magnetic field, at the edge more than at the center of the cathode.

3.2.2-b The Current Density Distribution over the cathode fall thickness

Determination of the cathode fall dimensions (thickness) of the abnormal cathode fall region is considered theoretically elsewhere in one of our previous studies[12], by a comparison between the theoretical formula and the experimental results in the presence and in the absence of the magnetic field. We can get an expression for the current density [13], as follow:

$$\frac{J_c}{P^2} = \left\{ \frac{4[1+(\omega/\alpha)]\varepsilon_o \left(\frac{e\lambda_i}{M}\right)^{1/2} V_c^{3/2}}{(P.d_c)^{5/2}} \right\} \qquad (5)$$

Where J_c is current density for the cathode fall region , ω/α is the average number of secondary electron produced per ionizing collision in the gas, e is charge of the electron, ε_0 is permittivity of free space, α is first Towsend ionization coefficient , M is mass of the ion, λ_ι is mean free path of ion , where d_c cathode fall thickness can be calculated from the following relation :

$$d_c = \frac{1}{\alpha} \ln\left[\frac{1+(\omega/\alpha)}{(\omega/\alpha)}\right] \qquad (6)$$

In many discussions **[14]** the ratio α/E is very useful since it represents physically the number of ions produced by electron collision per unit electric field. This ratio is designated ionization efficiency , η , and is given by:

$$\eta = \alpha/E = \frac{\alpha/p}{E/p} = \frac{A\ P\ e^{-Bp/E}}{E} \qquad (7)$$

Then α can be calculated using equation (7), furthermore substitute with α values into equation (6) to get values of the cathode fall thickness (d_c) [15]

Figures(10) and (11) show the relation between values of the cathode fall thickness(d_c), as a function of J/p^2, for He gas, in the presence and in the absence of the magnetic field, respectively. Where d_c (thickness of the cathode fall region) decreases as the current density increase. Furthermore the experimental data agrees, reasonably, with the theoretical curves. The main effects of the magnetic field on the present measurements are summarized in the following :

1- The rate of plasma loss by diffusion can be decreased by a magnetic field [16], then the current and current density increase in the presence of the magnetic field as shown in Fig. (10).

2- If D is the diffusion coefficient in the absence of the magnetic field and $D_\perp$ is the diffusion in the presence of the magnetic field, thus

$$D_i = KT/m\nu = \frac{\sqrt{KT}}{N_n < Q >_{i-n}} \frac{1}{\sqrt{2m_i}} \quad (8)$$

KT is Temperature in eV, N_n is equal to 3.55×10^{16} P where P in mbar, $<Q>_{i-n}$ is the Cross section, m_i is Mass of ions, $\nu = N_n <Q>_{i-n} v$, where

$$D_{i\perp} = \frac{D_i}{1+\omega^2\ \tau^2} \quad (9)$$

A comparison between the equation (7) and (8) , show that_ in the presence of the magnetic field, the plasma loss due to diffusion for He is decreased more than those in the absence of the magnetic field. Then the current density increased but with different ranges, because of if the magnetic field increase (B=100 Gauss), then the diffusion decrease sharply ($D_\perp$ decrease by $\cong 10^4$ times)

3.3 When magnetic field is applied, the cathode fall and negative glow regions are compressed, so higher values of potential are expected. It decreased the length of the cathode fall region(d_c). This effect is very powerful because electrons have beam-like properties in this region . This is very clear in Figs. (10),(11), where the cathode fall region reduced . This will of course increase the electric field in this region and thus ions would accelerate more and efficient sputtering would increase.

4- **CONCLUSION**

The thickness of the CF region (d_c) was determined in magnetized low-pressure Helium glow discharge. Where experimental results cover experimental pressure range from 1–4 mbar only, because of at less than 1 mbar, the axial potential distribution has been measured by single probe, suffer difficulties to initiate at the edge due to the reduction of the cathode fall, in addition the sheath , dust plasma and contamination around the probe leads to difficulties in measuring the potential between the probe and the cathode.
Two independent methods namely The axial potential distribution method defined accurately the thickness of the cathode fall region (d_c) was about 2.5-3.5 mm. depends upon the gas pressure (P). The data agree fairly with the second method namely theoretical and experimental for the current density of ions (J) distribution method of ions, was about 2.5-3.9 mm. Depending upon the gas, pressure (*P*) has

been obtained in the presence and the absence of the magnetic field either at the edge or the center of the cathode. It is concluded that a notice reduction of the CF thickness (about 20%) has been found in the presence of the magnetic field at the center of the cathode and (about 37%) at the edge. Thus, a stronger electric field is produced and consequently more acceleration of the ions is expected that enhances the sputtering processes rate of the cathode surface.

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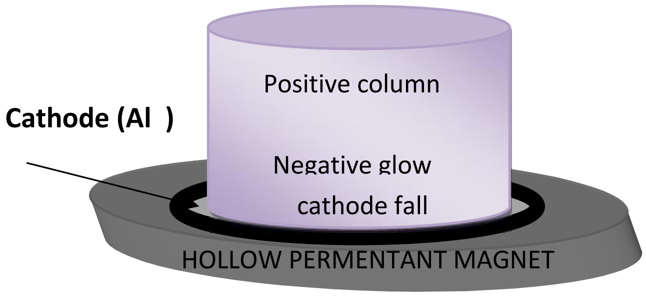

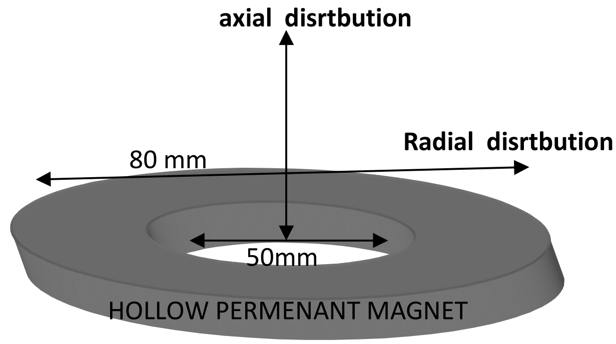

Figure (1.a) **Figure (1.b)**

Figure (1.a,b): (a) A schematic diagram of the plasma cell , (b) the radial and axial distribution for the magnetic field strengths

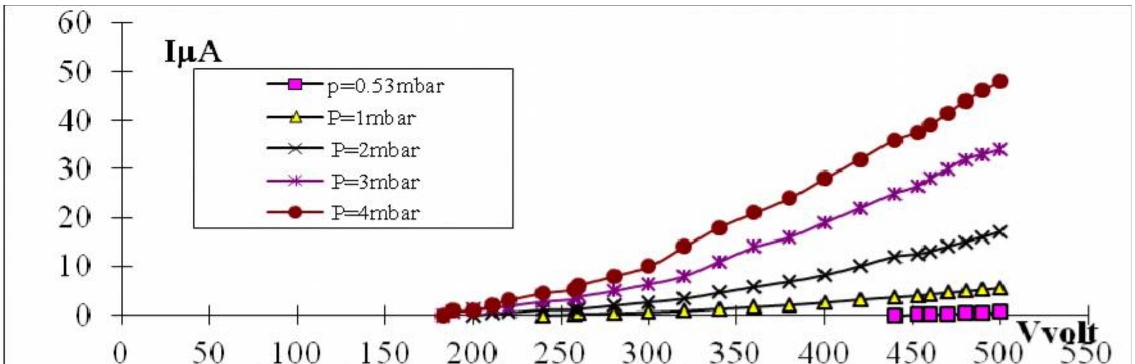

Figure (2): The (Ia-Va) characteristic curves of the Helium gas discharge at different pressures, In the absence of the magnetic field

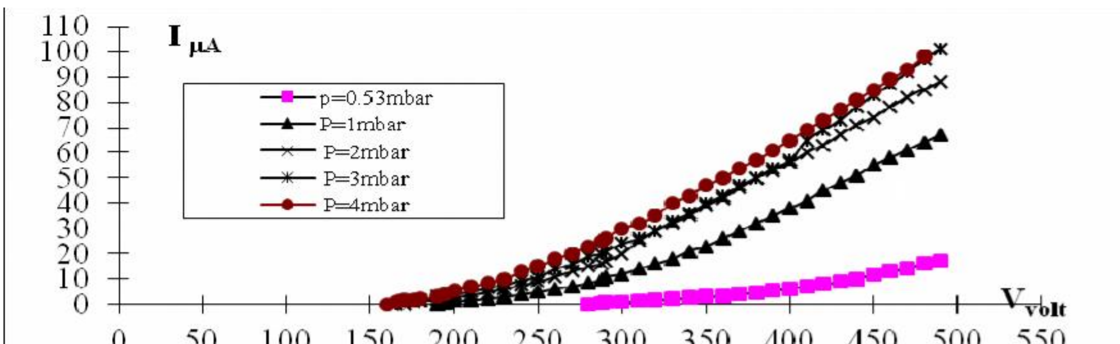

Figure (3): The (Ia-Va) characteristic curves of the Helium gas discharge at different pressures, In the Presence of the magnetic field

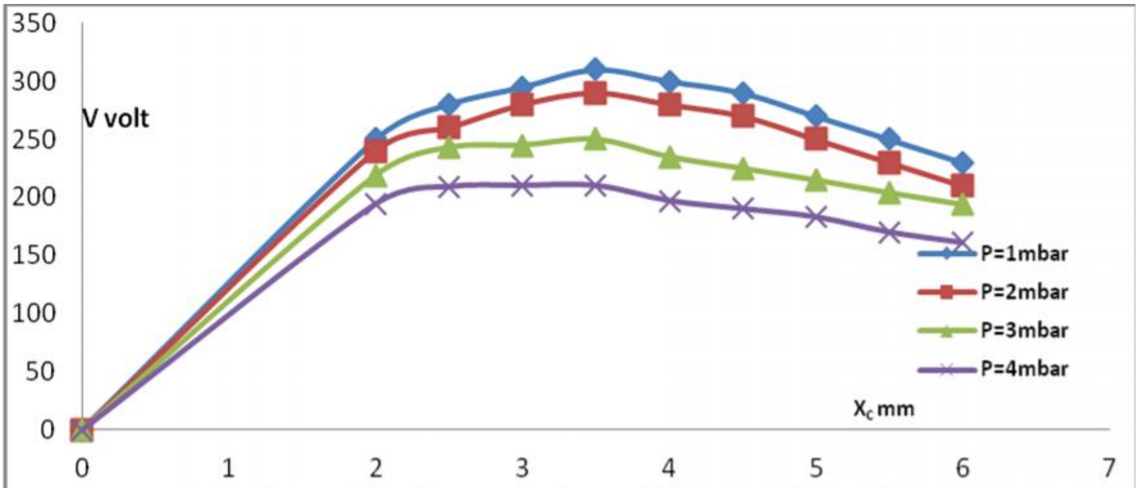

Figure (4): axial potential distribution in the absence of the magnetic field at edge and at constant current (I=10mA) for Helium

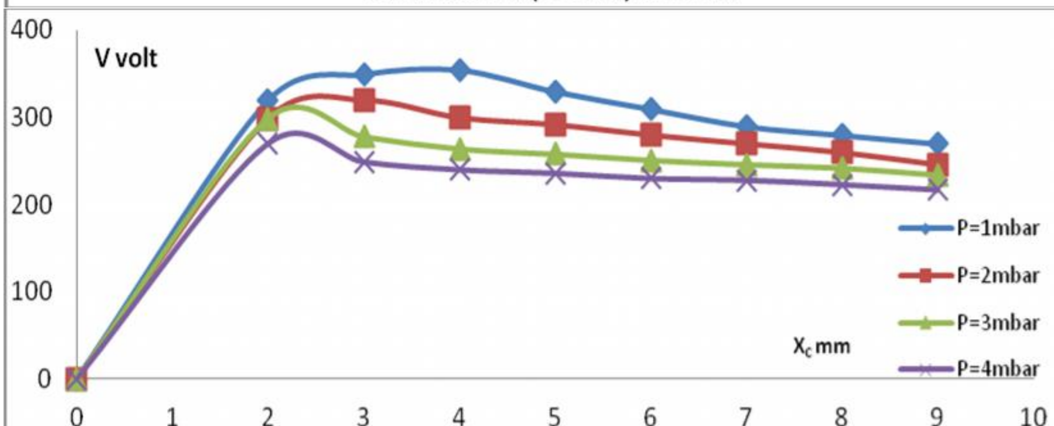

Figure (5): axial potential distribution in the presence of the magnetic field at edge and at constant current (I=10mA) for Helium

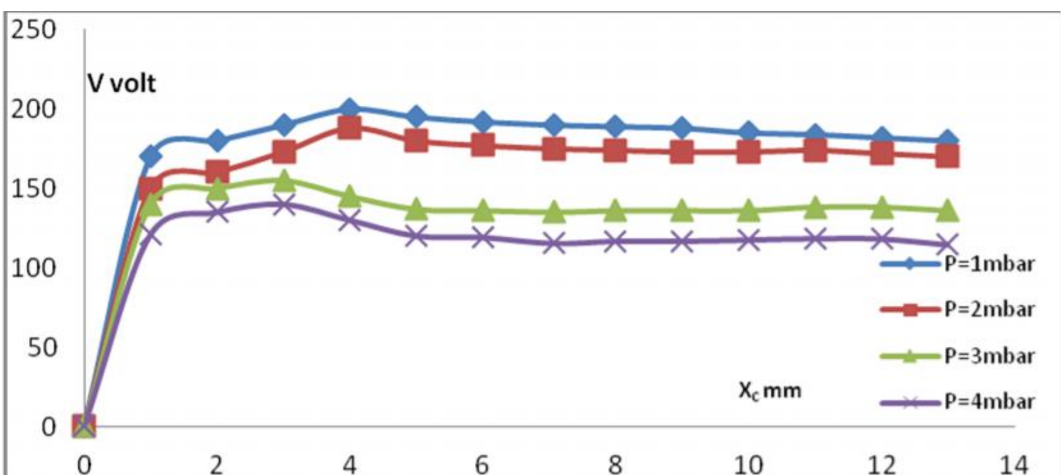

Figure (6): axial potential distribution in the absence of the magnetic field at center and at constant current (I=10mA) for Helium

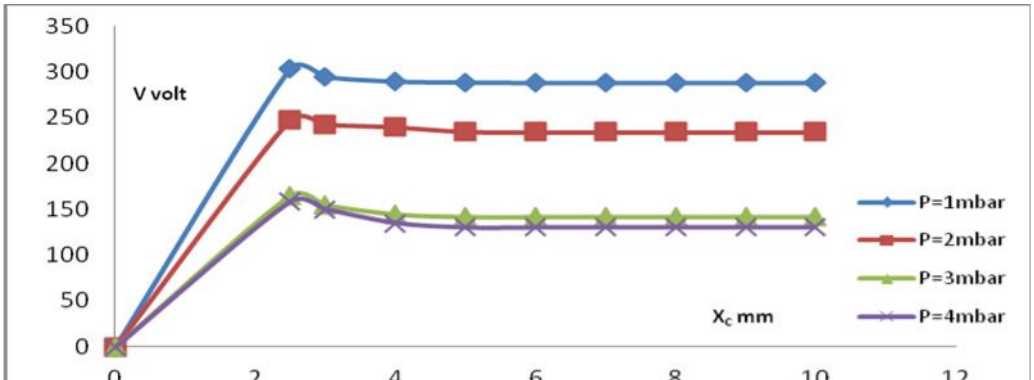

Figure (7): axial potential distribution in the presence of the magnetic field at center and at constant current (I=10mA) for Helium

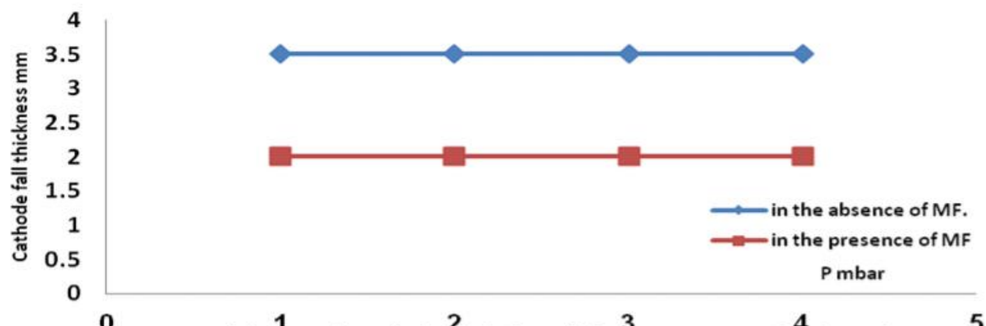

Figure (8): shows the cathode fall thickness (d_c) measurements at the edge in the presence and in the absence of the magnetic field at different He gas pressure

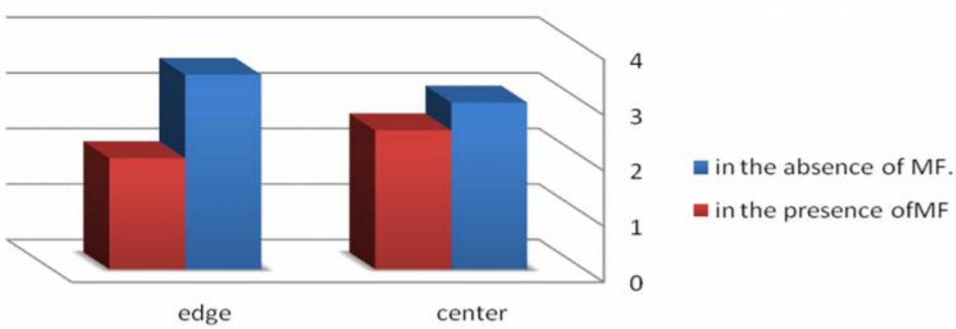

Figure (9): the thickness of the cathode fall (mm)in the presence and in the absence of the magnetic field, at the edge and at the center, of the cathode at Pressure 2mbar

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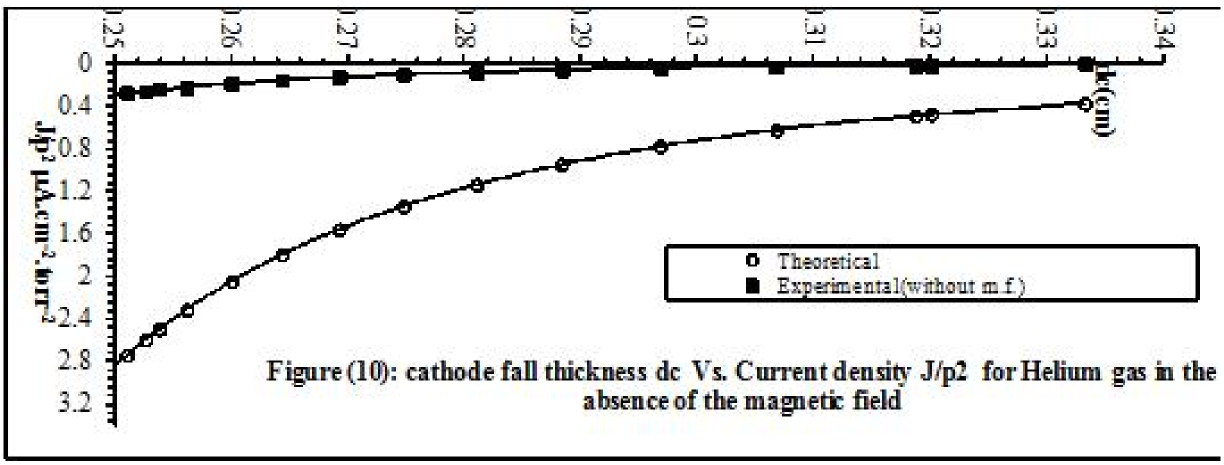

Figure (10): cathode fall thickness dc Vs. Current density J/p2 for Helium gas in the absence of the magnetic field

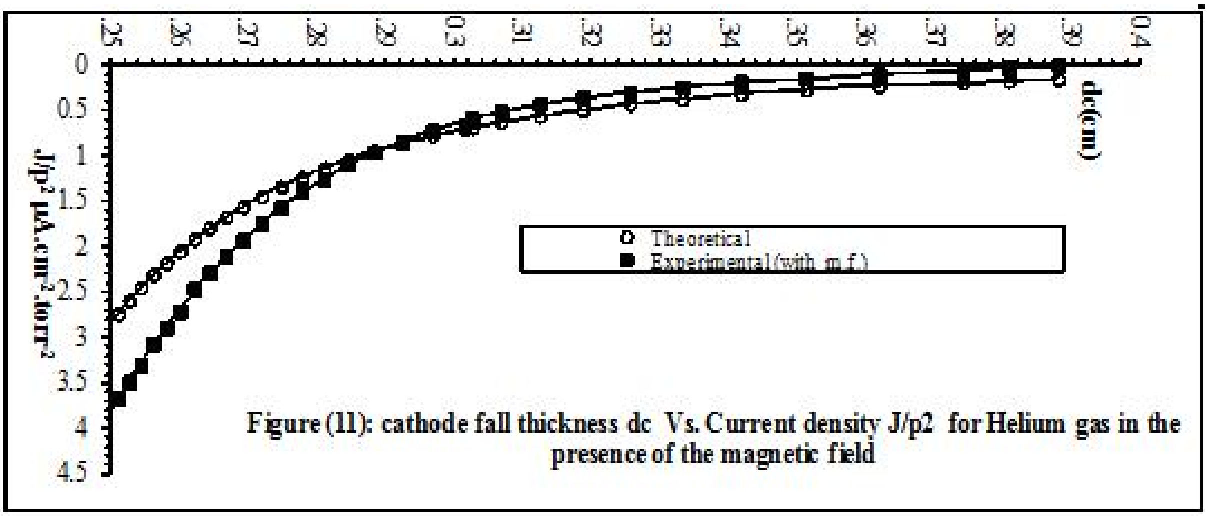

Figure (11): cathode fall thickness dc Vs. Current density J/p2 for Helium gas in the presence of the magnetic field