

Similarity of Gas Percentage and Strength of Magnetic Field on the Electrical Characteristics Control of dc Plasma

Abstract: For nitrogen gas discharge, the control of argon percentage in (Ar-N₂) gas mixture and in different magnetic field strengths, both separately in effect were investigated the electrical characteristics of DC plasma at constant low pressure ($P=0.7$ torr). Under the influence of Ar gas mixture percentage (Ar%) or different magnetized discharges (B+), the plasma parameters were measured such as the discharge current-voltage curves, Paschen's curves, breakdown voltages, potential distribution, electric field distribution, and the cathode fall thickness (Z_c) using the axial potential distribution method, it is noticeable that a reduction of (Z_c) about 22% due to applied B+ more than the case of applied Ar%. Moreover the electron energy distribution function (EEDF), electron temperature, and electron density were measured using single Langmuir probe, where electron temperature decreased about 38% for B+ more than Ar%, taking into account, general trend that values of T_e and N_e are inversely proportional, where electron density increased about 37% for B+ more than Ar%. Furthermore a non-Maxwellian EEDF was observed due to two groups of electrons were detected in the case of Ar%, in contrast, a Maxwellian EEDF was found in the case of B+ due to one group of electrons.

Keyword: nitrogen gas discharge- argon percentage of (Ar-N₂) gas- magnetic field - DC glow discharge-plasma parameters.

PACS NO.: 52.50.-b

1- INTRODUCTION

In recent years, plasma technology has evolved considerably and jumped a wonderful and big steps in many fields where gas discharge plasma present a considerable interest for a wide range of applications such as etching and coating treatments, air pollution control, sterilization and other applications [1-2].

Under low pressure discharges, the study of hydrocarbon-nitrogen mixtures with and without noble gases (argon, helium, neon, xenon, krypton) is carried out with a great importance due to their wide application in production of carbon nitride materials [3-4].

The electrical characteristics of DC Nitrogen-Hydrogen mixture glow discharge and the discharge current-voltage (I-V) characteristic curves of the discharge were measured at different gas pressures and gas mixture percentage [5]

Addition of inert gasses such as argon, neon and helium in nitrogen plasma, enhances the concentration of active species through penning excitation and ionization processes was investigated [6]

As expected, the discharge in mixtures of atoms with strongly different atomic masses offers new possibilities of forming dust structures in the gas discharge. Due to the

decrease in the concentration of intrinsic gas atoms, the frequency of ion-atom collisions with resonant charge exchange abruptly decreases, hence, the ion mean free path increases. Accordingly, the discharge parameters will also be different, i.e., the increase in the ion drift velocity and diffusion coefficient causes a decrease in the ion density due to rapid ion drift to walls [7-8].

The thickness of the cathode fall region in magnetized DC argon plasma has been investigated theoretically and experimentally [9-10] using two different methods namely: - the axial potential distribution and the current density distribution along the glow discharge regions

The localized plasma parameters have been investigated using Langmuir Double probe in the three regions of the discharge, such as the electron temperature (T_e) and the electron density (N_e). The parameters measured under the influence of external magnetic field [11].

The electron energy distribution functions in the cathode fall and negative glow regions of the Ar and He glow discharge were measured using a single Langmuir probe [12]. Two groups of electrons having different temperatures were detected in these two regions for both gasses. The presence of these two groups was attributed to a "runaway" process in the weakly ionized gas in which the conditions for electron acceleration without inelastic collisions were well satisfied. The electrons collide with neutral atoms in the negative glow region and produce secondary electrons of different temperatures.

The aim of the present work is to study, for nitrogen gas discharge, the comparison between the change effect of Ar percentage (Ar%) and different magnetic field strengths ($B+$) on the electrical characteristics of (N_2 -Ar) mixture glow discharge such as the discharge current-voltage curves, breakdown voltages, applied electric field values, electron temperature, electron density and the cathode fall thickness (X_c), also determination of EEDF using single Langmuir probe technique at different $B+$ and different Ar% in (N_2 -Ar) gas mixture.

2- THE EXPERIMENTAL SETUP

Figure (1a and b) shows a schematic diagram of the experimental setup. The cylindrical discharge cell is a stainless tube of 25 cm length and 10 cm diameter. The two parallel, circular and movable electrodes are enclosed in the discharge cell and made of copper, where the copper metal is chosen according to good and perfect sputtering purposes. The discharge cell is evacuated to a base pressure of 7 mtorr using two stage rotary pump, the cell was filled with the working gas (argon and nitrogen gasses) where two needle valves were used to control. The flow rate of the gas mixture inside the cell, taking into account that the working pressure gasses were low. The applied electrodes voltage was controlled by a DC power supply which can produce potential up to 1000 V and current up to 100 mA.

In this study an electric single probe, Langmuir probe [13], inserted into the plasma, and a potential V_p is applied to the probe. The probe made of molybdenum wire (of 0.3 mm diameter) was used. The wire is isolated by a thin glass tube. A tip of 2 mm length of the wire is immersed in the discharge tube. Experimental procedures, the apparatus used for single probe, the working principle, typical IV characteristic curve of the single probe, and the electron energy distribution functions (EEDF) theory, are identical to our previous study that was carried out [14].

Electron energy distribution function (EEDF) was determined in the present work at different percentages (Ar %) in the (Ar-N₂) gas mixture and at different (B+) using single probe technique for the analysis of the measurements.

Many hollow permanent hollow circular magnets, with 30 mm diameter, are placed below the cathode electrode to produce the magnetic field measured by fully portable hand-held Hall effect gauss meter. The diameter dimension of the magnet are less than those of the target, where each of them with a very small centered hole with 5 mm diameter.

3- RESULTS AND DISCUSSION

3.1 THE I-V CHARACTERISTIC CURVES OF THE GLOW DISCHARGE

3.1(a) under the influence of different argon percentage Ar%

Figure (2) shows the (I-V) characteristic curves of the Nitrogen gas discharge at low pressure 0.7 torr and at different argon percentage (40, 60, 80 and 100%) in (Ar-N₂) gas mixture, whereas the distance between the two electrodes was fixed at (3 cm). The increases of the electrical current by the increases of Ar percentage in (N₂-Ar) mixture can be explained as follows [15]:

- At low value of Ar percentage (40%), 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 is expected. With increasing the percentage the 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.

3.1(b) under the influence of different external magnetic fields (B+)

- 1- the magnetic field strength B measured by a Hall probe which moving along the cathode surface from one edge to the other (30mm) passing through the hole at the center of the magnet for the radial distribution as shown in Fig.(3a), where the magnetic field strength B is maximum at the two cathode edges and is a minimum at the center of the cathode (the center of the hollow magnets) where the magnetic field strength B is very weak, furthermore B increases as number of the magnet increases. On the other hand, Fig.(3b) shows the axial distribution along the discharge tube when the Hall probe moved from the edge of the cathode to the edge of the anode. The magnetic field strength B is maximum at the edge of the cathode fall region then it decrease to positive column passing through the negative glow region.
- 2- On the other hand the situation is the same behavior for the (I-V) characteristic curves under the influence of different external magnetic fields (B+) for N₂ gas discharge, whereas number of magnets increases, the magnetic field strength increases from (140-251-390-536 mT) as shown in Fig.(4), the curves are similar behaviors to those at Ar%. The decrease of the discharge voltage as the magnetic field strength increase from magnet one results to magnet four results may be referred to the increase in the number of collisions between the

primary electrons and neutral gas atoms due to increasing of the magnetic field strength from 140 mT to 536 mT.

- 3- Values of the discharge current of B+ are smaller to those in curves of Ar%. Thus, slopes of the (I-V) curves for B+ are smaller than those in curves of different A%, (i.e. the resistance of the discharge is larger when no magnetic field is applied).

3.2 BREAKDOWN VOLTAGE

Figure (5a) represents the breakdown voltage (V_b) as a function of Ar percentage (Ar%) in (N₂-Ar) the gas mixture at different argon mixture beginning with (40%) until 100%. For Ar%, It is clear evidence that, the breakdown voltage V_b , will be decreased by increasing the percentage of argon gas which follows the left-hand side of Paschen's curve.

The breakdown voltage decreases by an additional increase in Ar percentage of the mixture until a certain value (60-80-100%), which then leads to a further increase in the breakdown voltage. As far as it is known, the breakdown curves of the glow discharge are described by Paschen's law, i.e. the breakdown voltage depends on the electrode spacing ($d=3\text{cm}$) and the gas pressure ($P=0.7\text{torr}$) as follows [16]:

$$V_b = \frac{bPd}{\ln(aPd) - \ln[\ln(1 + \gamma^{-1})]} \quad (1)$$

where, a and b are constants, which can be regarded as constants for a certain kind of gas, and γ is the secondary electron emission coefficient of the electrode.

For B+ discharge, Fig.(5b) shows that the breakdown potentials (V_b) of the discharge decreased also when the applied magnetic field is increased and nearly the same general behavior and have fewer V_b values than those of Ar% discharge,

3.3 AXIAL POTENTIAL AND ELECTRIC FIELD DISTRIBUTIONS

The axial potential distribution as a function of distance from the cathode has been measured along the axis of the discharge tube using single probe also by taking the gradient of the plasma potential determines the electric field distribution that is responsible for energizing the electrons, which maintain the discharge through ionization.

Figure (6a) represent samples of the axial potential distribution as a function of mixing percentages of Ar by (40%-60%-80%-100%). 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 rapidly due to the existence of the reversal field in the negative glow and at the beginning of Faraday dark space [17].

Also the axial electric field distributions for argon percentage of (Ar-N₂) gas mixture. Fig (6b) represent samples of the electric field distribution, where due to the large potential drop in the cathode dark space, the axial field in this region is rather high and goes more or less linearly to virtually zero at the end of the cathode dark space region. So that it may be a good representative for the thickness of the discharge regions. The shapes of the electric field distributions do not significantly change with mixing percentage.

For different magnets with different magnetic field strength B, give the same trend, and quite similar for figures of argon percentage in (Ar-N₂) gas mixture of axial potential and axial electric field distributions.

3.4 The CATHODE FALL THICKNESS MEASUREMENTS

Figure (7a) shows cathode fall thickness values, which measured from the potential distribution curves, as a function of Ar% and a function of B+. It can be seen from figure that the cathode fall thickness (Z_c) decreases from 5 to 2.5 mm with increasing mixing percentage of (Ar%) from 40 to 80% and from 4 to 1.9 mm by increasing magnetic field strength B(B+) from 140mT by one magnet to 536 mT by four magnets. Also it is noticeable from Fig.(7b) that values of Z_c for (B+) is less than those of (Ar%) in spite of the breakdown voltages for (B+) are more than those of (Ar%).

For Ar%, The decreases in Z_c as (Ar%) 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 [18].

For B+, when the magnetic field is applied (B+), the cathode fall and negative glow regions are compressed, so higher values of potential are expected when the magnetic field strength is increased and hence the length of the cathode fall region (Z_c) is decreased. This can be explained as follows:- due to using magnets, the plasma will be confined near the cathode, then the current density can be increased by the magnetic field, due to the effective increase in the gas pressure where the apparent increase in pressure P (in torr) is given by ΔP whereas :-

$$\frac{\Delta P}{P} \cong 10^{-2} \frac{\lambda}{M T_i} \left(\frac{H}{P} \right)^2 \quad (2)$$

Where λ is the mean free path for ion in cm, at P= 1 torr, P is the gas pressure in torr, T_i is the ion temperature in K⁰, M is the molecular weight and H is the magnetic field in orested. This shows 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 [19].

3.5 ELECTRON ENERGY DISTRIBUTION FUNCTION MEASUREMENTS

The electron energy distribution function, EEDF, is significant and vital for understanding various plasma processes, such as electron impact ionization and excitation. In this study the EEDFs are considered according to Druyvesteyn formula [20]:

$$F(\varepsilon) = - \frac{4}{e^2 A_p} \left(- \frac{m_e V_p}{2e} \right)^{1/2} \frac{d^2 I_e}{dV_p^2} \quad (3)$$

The second derivative was estimated by differentiate the probe current I_e twice, where A_p and V_p represent the probe area and voltage, respectively

Figure (8a) shows the measured (EEDFs) as a function of Argon as inert gas mixing percentage in Nitrogen plasma. The plots indicate that (EEDFs) have two peaks for

the low percentage of argon 40% and 60%, represents two groups of electrons with different energies. The electrons in the first group, with low energy, affect local electron densities and the local plasma conductance. The electrons in the second group, with high energy, play the main part in the local excitation and the local ion production [21]. From the figure, it can be seen that there is a decided shift of the distributions to higher energy values as the argon percentage in the (Ar-N₂) mixture increased from 40% to 100%. The change in EEDF shapes with an increase in argon percentage in mixture plasma is due to the modification in various energy loss and gain reactions going on in the plasma. In addition to inelastic collisions of the electrons with molecules of argon. Moreover as argon percentage increases in the (N₂-Ar) mixture EEDF is shifted to high electron temperatures.

On the other hand typical curves can be obtained in Fig.(8b) which represents the EEDE as a function of magnetic field strength B (B+) represented from 140 mT by one magnet to 536 mT by four magnets, give the same trend and quite similar for figures of argon percentage (Ar-N₂) gas mixture, with the difference in the curves of magnetic field application give results with only one group of electrons appears and the distribution may be Maxwellian distribution as magnetic field strength increases in N₂ discharge, EEDF is shifted to high electron temperatures where magnetic field can confine the energetic (ionizing) electrons to a small volume near the cathode electrode, then decreased the cathode fall region thickness and the rate of plasma loss by diffusion must decrease. Moreover electrons from the cathode that pass through the cathode sheath region without collisions and ions being virtually unaffected. Furthermore, for B⁺ case, the thermalization time was short enough for electrons to redistribute themselves in one Maxwellian distribution group [22].

3.6 THE ELECTRON TEMPERATURE AND ELECTRON DENSITY

Figures 9(a and b) show the measured change of electron temperature T_e, and electron density N_e, as a function of Argon as inert gas mixing percentage in Nitrogen plasma Ar% and also a function of different magnetic field strength B+, respectively in the cathode fall region (C.F.),

As Ar% and B+ increased, T_e decreased and N_e increased, where values of T_e varied from 6.5 to 5 eV for B+, and varied from 4 to 3.12 eV for Ar% and Furthermore, values of N_e varied from (8 to 9.5) ×10⁹cm⁻³ for B+, and varied from (5 to 6.5) ×10⁹ cm⁻³

The possible explanation is when argon percentage is added and increased the nitrogen discharge, there is a sharp increase in electron density and hence a higher electron-electron collision frequency, which always tend to deplete electrons in the "hot tail" and the EEDF relaxes finally to Maxwellian. As a consequence, T_e decreases [23].

On the other hand in the presence of magnetic field as B+ increased, the electron move in helical path and the path increases as the magnetic field strength increased, then the electrons thus move a much longer total distance in the gas in the order to move a given distance in the direction of the electric field. They hit gas atoms more often and thus have a greater chance of ionization, then the electron temperature decreased more than those in the Ar%

4- CONCLUSION

Our fashion work is the comparison between the effect of different admixture of Argon to nitrogen (Ar%) and the effect of magnetic field strength increments B^+ due to small hollow circular solid permanent magnets of few hundred of Millie tesla (mT) below the cathode (the target electrode) on the electrical characteristics control of dc plasma

The molecular and atomic forms of these gasses (Argon and nitrogen have different excitation and ionization energies. Therefore, it is very often possible that the excited state of one form can ionize the other form (Penning effect) and causes the increase in the discharge current at the same voltage

In general, a glow discharge is found to be stable only in a low-pressure discharge of less than a few mbar as in our experiment $P=0.7\text{mbar}$, this is because when the pressure is rising, the discharge shifts to sparks and arc and thus, making it impossible to uniformly process an object

Nitrogen gas discharge was studied through our article by the comparison between the effects of (Ar%) and of (B^+) on the electrical characteristics of (N_2 -Ar) mixture glow discharge. A similarity effect due to both (B^+ and Ar%) on the electrical characteristics control of dc plasma and it is noticeable that the rate of plasma loss by diffusion can be decreased by increment of magnetic field strength more than that due to the effect of argon percentage increments, then the current and current density increases in the presence of the magnetic field.

The breakdown voltages as a function of Ar% were more than those as a function of B^+ by 17%, the cathode fall thickness (X_z) as a function of B^+ is more than those as a function of Ar% by 22% also,

Moreover the electron energy distribution function (EEDF), electron temperature, and electron density were measured using single Langmuir probe, where electron temperature decreased about 38% for B^+ more than Ar% and electron density increased about 37% for B^+ more than Ar%. A non-Maxwellian EEDF was observed in the case of Ar%, in contrast a Maxwellian EEDF was found in the case of B^+ .

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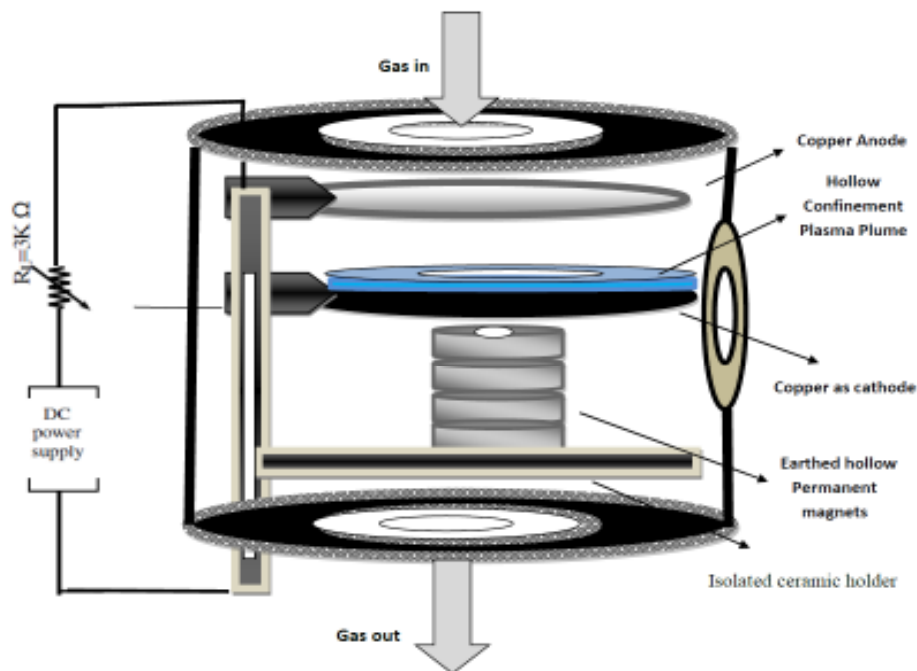


Fig. (1a) : A Schematic diagram of the plasma cell

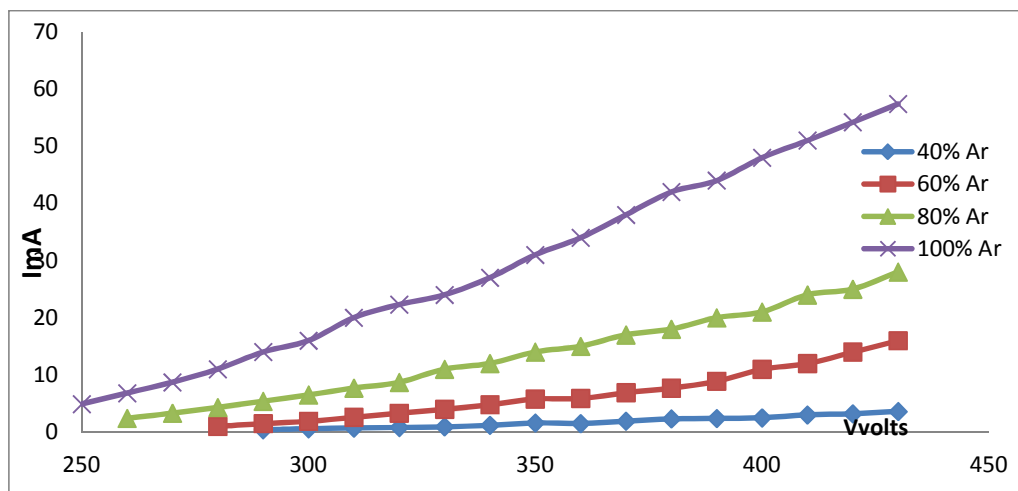


Fig.(2) I-V characteristic curves of the nitrogen gas discharge in the low pressure 0.7 torr and at different argon percentage

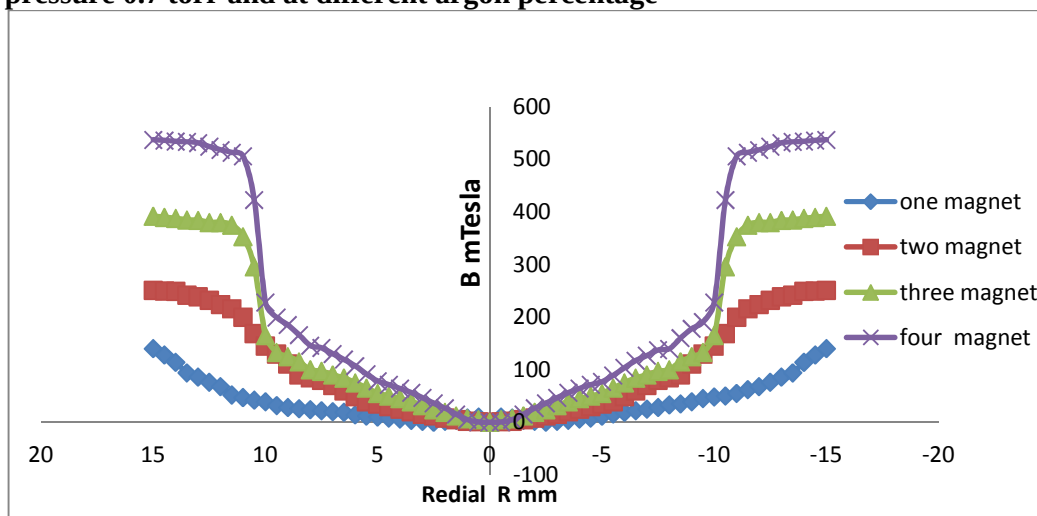


Fig.(3a)Radial distribution of different magnets with magnetic field strength B

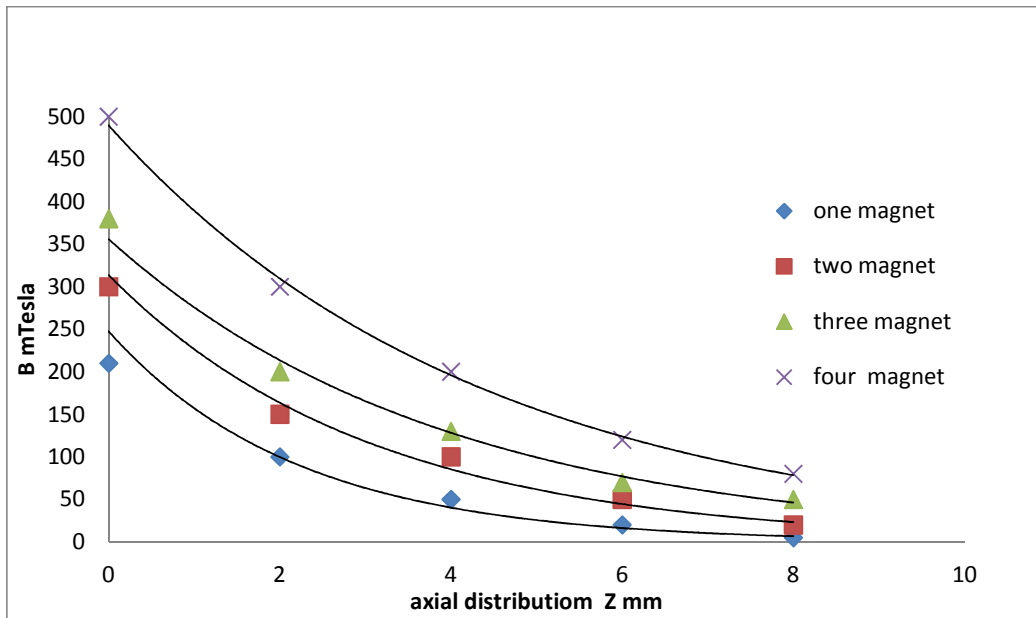


Fig.(3b) Axial distribution of different magnets with magnetic field strength B

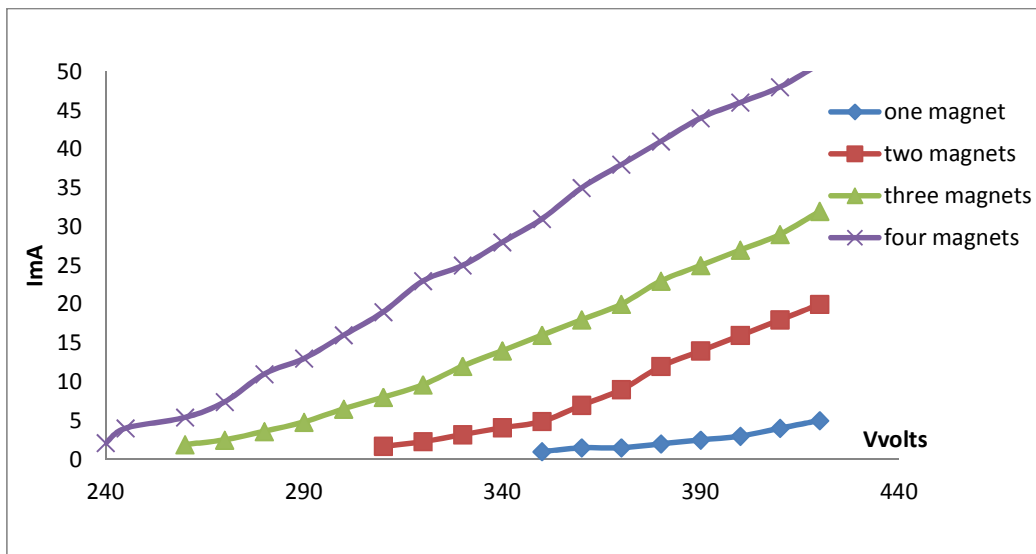


Fig.(4) I-V characteristic curves under the influence of different magnetic field strengths B+

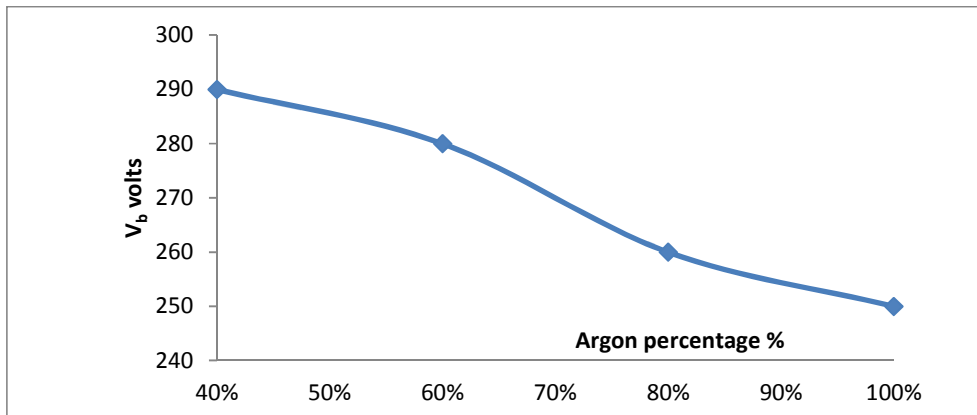


Fig.(5a) the breakdown voltage (V_b) as a function of Ar%

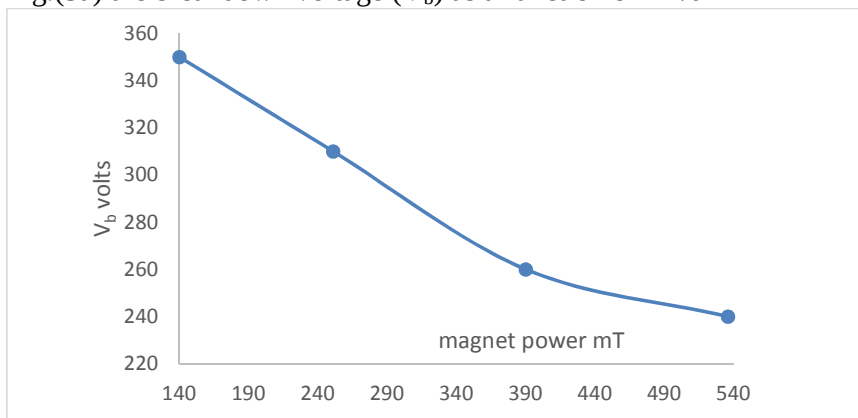


Fig.(5b) the breakdown voltage (V_b) as a function of B+

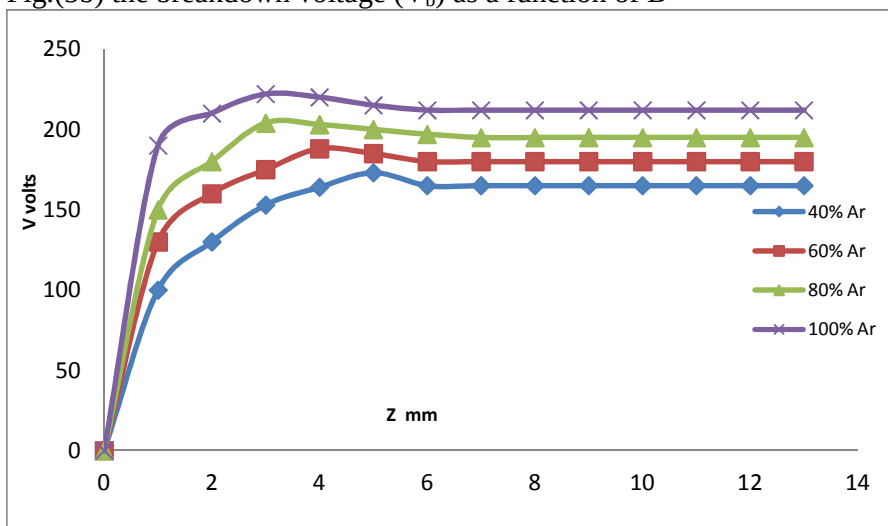


Fig.(6a) the axial potential distributions for different Ar percentage

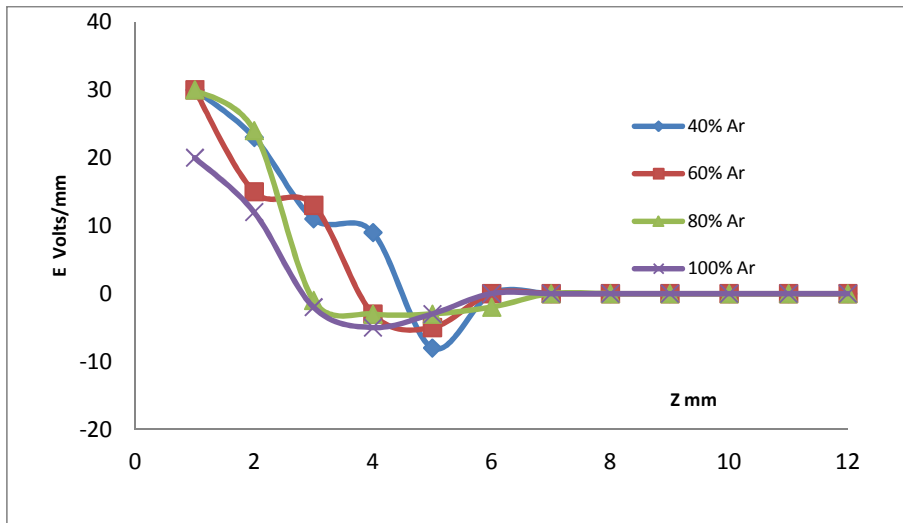


Fig.(6b) the axial electric field distributions for different Ar percentage

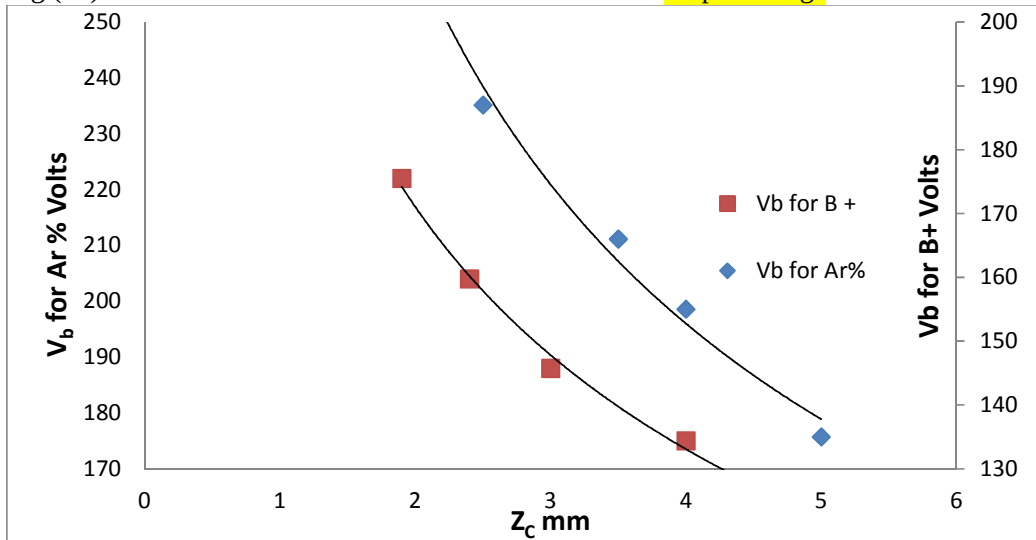


Fig.(7a) cathode fall thickness variation with breakdown voltage values of Ar% in the mixture and values of B+ with 0.7 torr filling pressure.

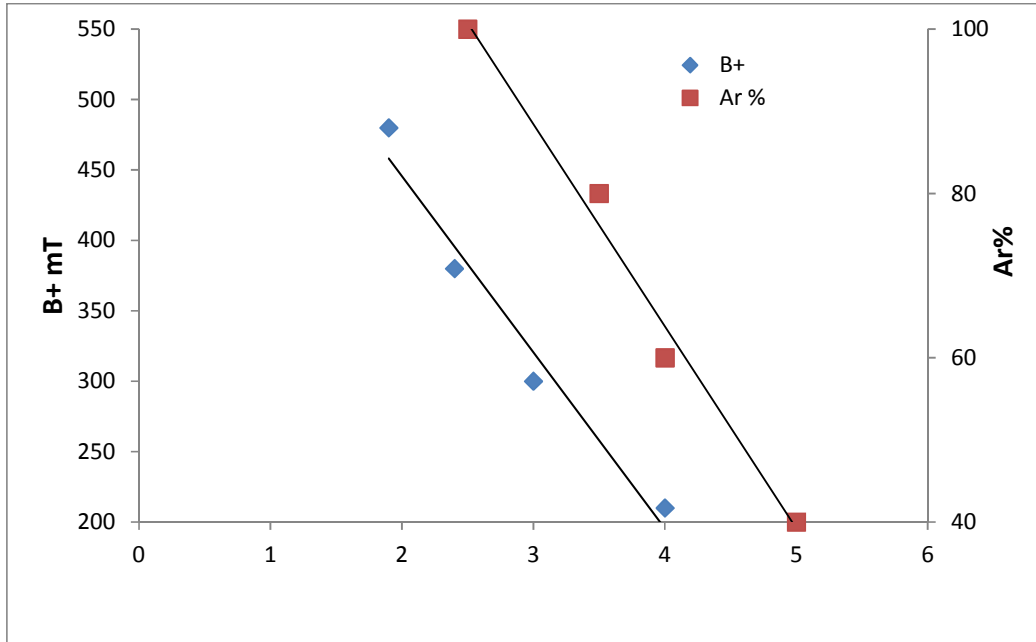


Fig.(7b) cathode fall thickness variation with Ar% in the mixture and B+ with breakdown voltage values with 0.7 torr filling pressure.

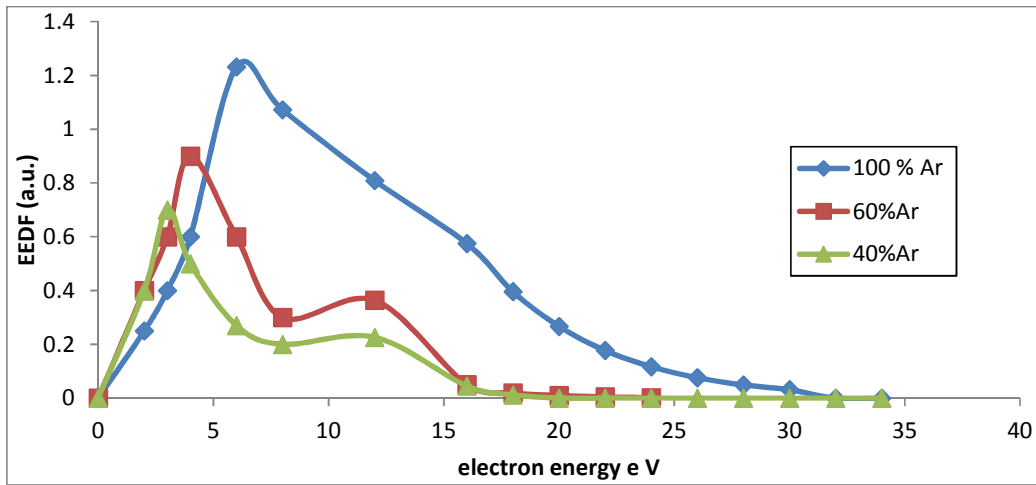


Fig.(8a) Electron energy distribution function in the cathode fall region, discharge in N_2 for Ar%, $P = 0.7$ torr.

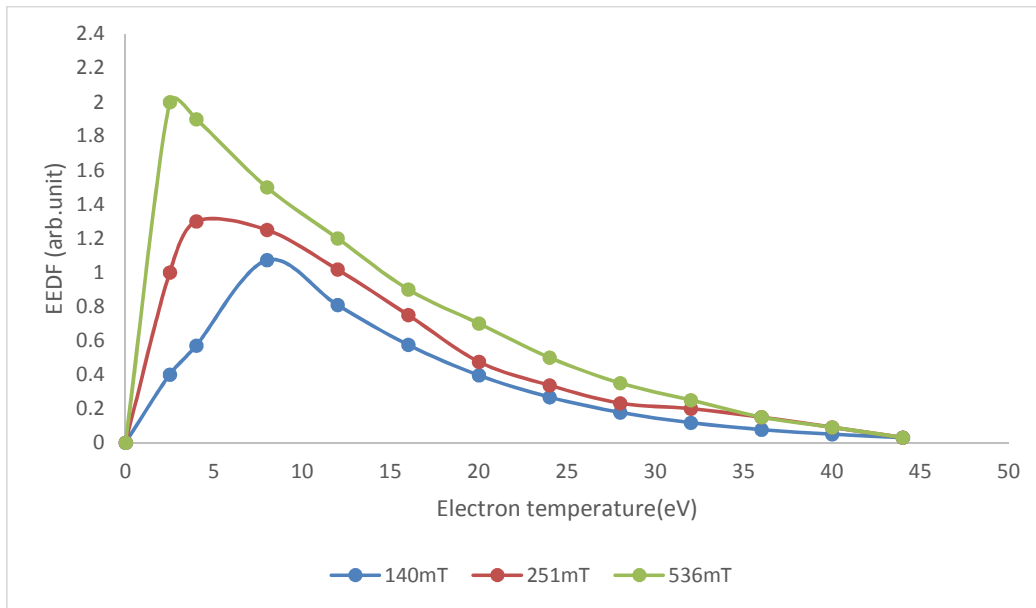


Fig.(8b)Electron energy distribution function in the cathode fall region, discharge in N_2 for B^+ , $P = 0.7$ torr.

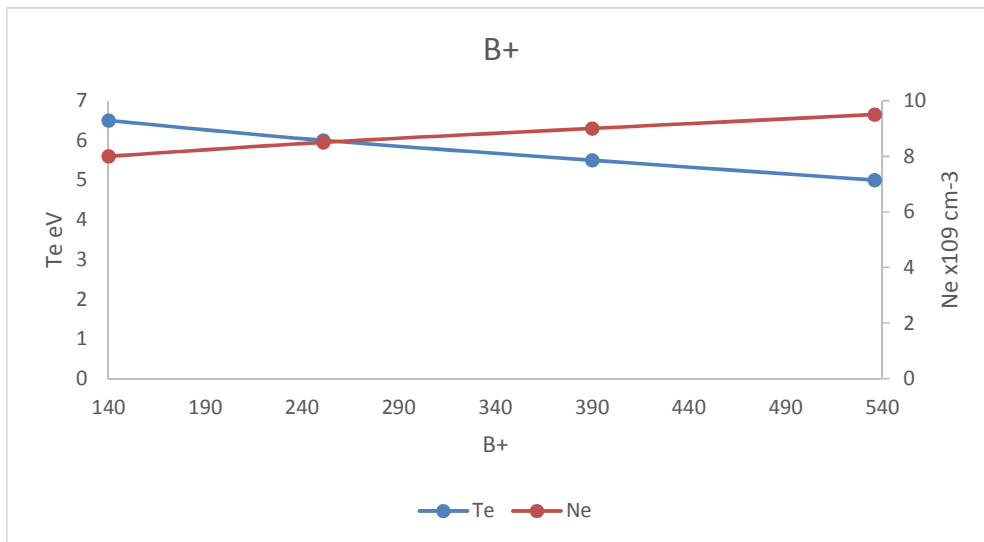


Fig.(9a) Distribution of the electron temperatures and densities due to B^+ for N_2 discharge

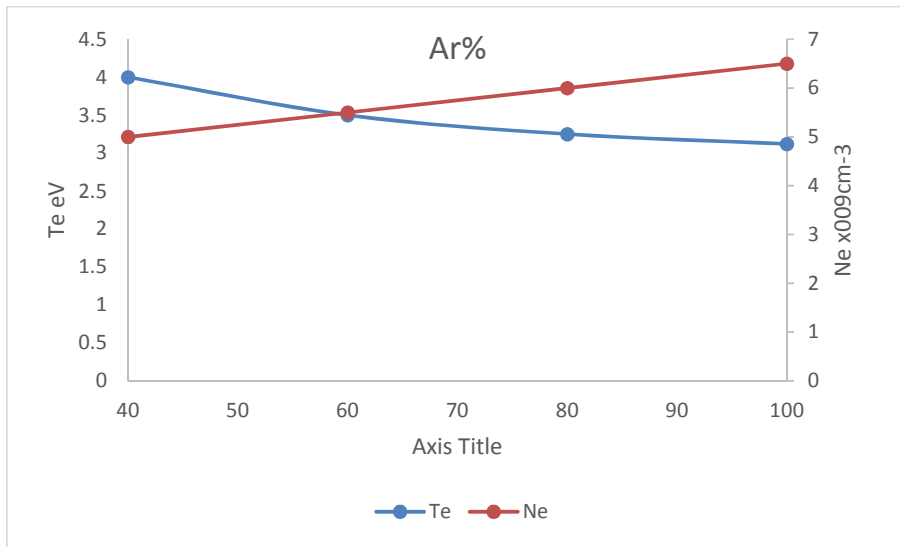


Fig.(9b) Distribution of the electron temperatures and densities due to Ar% for N₂ discharge