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Theoretical and Experimental Investigation of Hollow Cathode Nitrogen Glow Discharge Plasma

[1]Shamoo Kh. AL-Hakary, [2]Ahmed Fata Abdurrahman Amedi and [3]Luqman M.S. Dosky
[1,2, 3] University of Zakho, Faculty of Science, Department of Physics

Abstract: - An experimental investigation of a DC hollow cathode nitrogen glow discharge has been done at different gas pressure ranged from (0.075 to 0.75) torr and different radial positions of discharge. Plasma properties were inferred from the current – voltage characteristics of the double probes positioned at different radial space of the discharge, moreover a computer program proposed to determine plasma parameters from the probe characteristics. Furthermore these parameters were calculated using the relation that electron temperature can be written as an explicit function of gas pressure and radius discharge at the Schottky limit. The result exhibits that the measured and calculated electron temperature varies nearly a decreasing exponential with gas pressure as a results of fitting , as well as the variations of both floating and plasma potentials close to the same behavior. On the other hand there is a good agreement between measured and calculated results, these in turn compared with reported works in previous studies and there is a satisfactory agreement.

Keyword: - Hollow Cathode, Glow Discharge Pressure, Plasma Parameters and Langmuir probe

I. INTRODUCTION

A hollow cathode glow discharge is a subclass of glow discharge and offers characteristics quite unique from that of a planar cathode. The hollow cathode effect, which is discovered by Paschen's in 1916 and subsequently developed for its use in a spectroscopic light source, J. Chen et al. (2002). Manifests itself in considerable increase in the discharge current and some decrease in the discharge voltage, arises at a specific proportion of the voltage to the distance between the cathode and the screen in glow discharge V.V .Budilov et al (2007). When a negative glow region facing the opposite cathode surface overlap, hollow cathode effect appears, this effect is the most specific feature of this devices D. Maric et al (2009). The widely accepted definition of hollow cathode effect is the enhanced emission from the negative glow within the cathode cavity as well as the increase in discharge current density, up to several orders of magnitude at constant potential as a result of the cathode geometry G.J.M Hagelear et al (2010). A great number of fundamental experimental on hollow cathode glow discharge have been performed in the past, of particular interest are those that report the electron behavior and plasma gas temperature, because these properties are no daubttied to the pressure, voltage and current characteristics of the plasma as well as to the excitation, ionization and sputtering processes, Eizaldeen F .Kotp and Ashwaq A.Al – Ojeery (2012). Experimental and theoretical studies of the electron energy distribution function in a stationary glow discharge with hollow cathode in nitrogen are performed by V.TU. Bazhenov et al (2001), a significant gap and respective inverse region appear on the EDF, which is due to vibrational excitation of N_2 molecules. J. Chen et al. (2002), made a development of hollow cathode micro plasma devices where using micromachining techniques, then compared with larger discharge devices**.** Linear current-voltage relationships are obtained. O. H. Chin and C. S. Wong (2002) investigated the dependence of the electron temperature, electron density and plasma potential of a d.c. helium hollow cathode discharge with product of the hollow cathode diameter and gas pressure. H. Shen et al.(2005) , generated a nitrogen beams with very high N^{+}/N^{2+} ratio using hollow-cathode discharge. The dependence of N^{+}/N^{2+} ratio in the extracted beams on the discharge parameters was studied by mass spectroscopy. V. Tsiolko et al. (2009) .presented an experimental measurements and numerical calculations of the electron energy distribution function in the plasma of a hollow cathode glow discharge in N_2:SF_6 mixtures. A.S. Bugaev et al.2010).Studied new design of self-heating hollow cathode. Such hollow cathode operates with lower gas flow rates than conventional cathode and has a longer lifetime. N.P Polueklov et al. (2012) used Langmuir and optical emission spectroscopy measurements to study a mechanism for the production of excited argon and copper atoms and ions. Plasma parameters as a function of the position, pressure and power were measured.

The aim of the present study is the calculation of plasma parameters using the relation that the electron temperature can be written as an explicit function of product of gas pressure and radius of the discharge in the Schottky limit (nearly high pressure). Furthermore to conform these results and to make a comparison, an experimental system of hollow cathode glow discharge is designed and double probes method is used to measure the plasma parameters at the same conditions of the theoretical calculations, as well as a computer program is proposed to determine these parameters from the double probes characteristics .

II. EXPERIMENTAL ARRANGEMENT

The discharge chamber is an open tube of Pyrex glass. The discharge tube is about 250 mm in length and 50 mm in diameter as shown in figure (1). Tow cylindrical rubber chambers discs used to input both electrodes through it and closing both sides of the tube to prevent leakage of gas from the tube. The distance between the electrodes is fixed to 140 mm. The tube was providing with two pipe connection, the first one was connected with the double needle valve which, the first valve is a gas inlet that is rotatable and another valve for rotary vacuum pump. The anode is made from a brass metal in shape cylindrical disk of diameter 40 mm and thickness of 1.4 mm is connected to the external electric circuit though the copper rod of length 70 mm fixed at the one end of the discharge tube by vacuum seal to prevent the leakage .

The hollow cathode is made also from copper metal of hollow cylindrical shape of inner diameter 34.95 mm and outer diameter about 42.95 mm and the thickness of hollow cathode is 2.55 mm and depth of 23.9 mm and 41.35 mm in length. The hollow cathode has been covered on the outer shell and the back side and edges by using Teflon insulator in order to restrict the discharge inside the hole of the hollow cathode.

The vacuum system consists of the rotary vacuum pump of the Lybold [Trivac E2, Pr.Nr.140000, Lybold], can evacuate the system to ultimate pressure $0.75*10^{-3}$ torr, the thermocouple vacuum gauge [Thermovac TM21],is used for measuring pressure and the needle valve to control the of argon gas flow. The required pressures for this study are ranged from (0.075-0.75) torr. The discharge chamber is connected to the vacuum system through a crossing piping unit. The four sides of this unit are connected to the vacuum gauge, rotary pump, and discharge chamber and to the vacuum needle valve. The commercial nitrogen gas of purity 99% has been used for this study to produce nitrogen glow discharge in such away by filling and evacuating the system many times to ensure that the chamber contain is the nitrogen gas with required pressure with minimum leaks as possible.

The double probes are made from a copper wire of radius 0.235 mm and length 6mm as well as insulated by capillary tube except 6 mm is inserted in to the plasma .The distance between the probes 12.1 mm and the probes apart 60 mm from the anode and 190 mm from the hollow cathode .The probes are passes through the big tube which is in turn pass through a vacuum seal these has been done in order to get easy movement of the probe. Then the double probe was connected to the external electrical circuit. The two probes were input to the discharge tube above each other until the two probes were worked in the same region. The double probes have been cleaned before each experiment in the same way as the anode and hollow cathode.

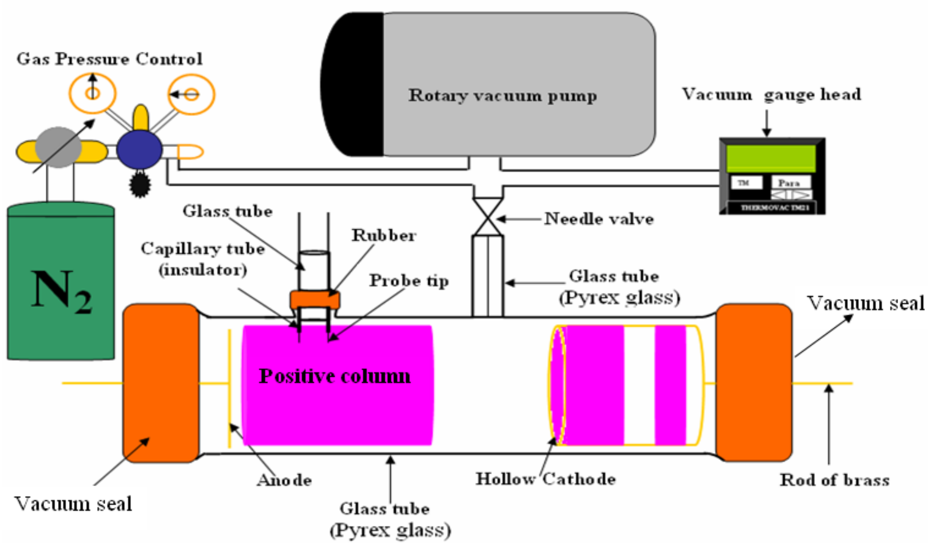

Figure (1) Glow Discharge System

The discharge was initiated by applying high voltage from two power supply (6kv), (2mA) connected in series sufficient for occurring glow discharge at different gas pressure for constant current. The non- linear protective resistor (Lamp) was used to limit the current and to protect the power supply from high voltage after breakdown. AC power supply of about 10V was used to bias the double probes and a direct resistance (1MΩ) is used to convert voltage to real value of current, the capacitor (7 pf) was used to reduce the phase difference in (I_p -V_p) double probes characteristics which observed on the oscilloscope screen, (figures 2 and 3) represent the discharge electric circuit and the double probes electric circuit. For more details see reference, A.F .Amedi. (2010).

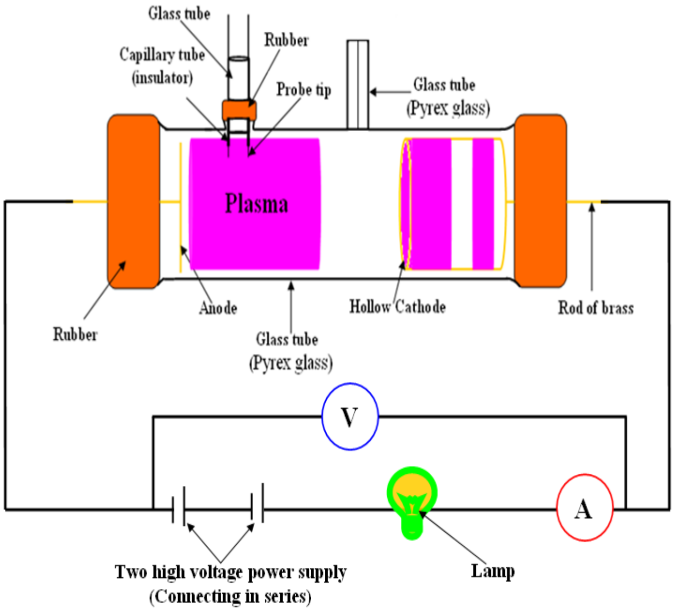

Figure (2) Electric Circuit of Glow Discharge

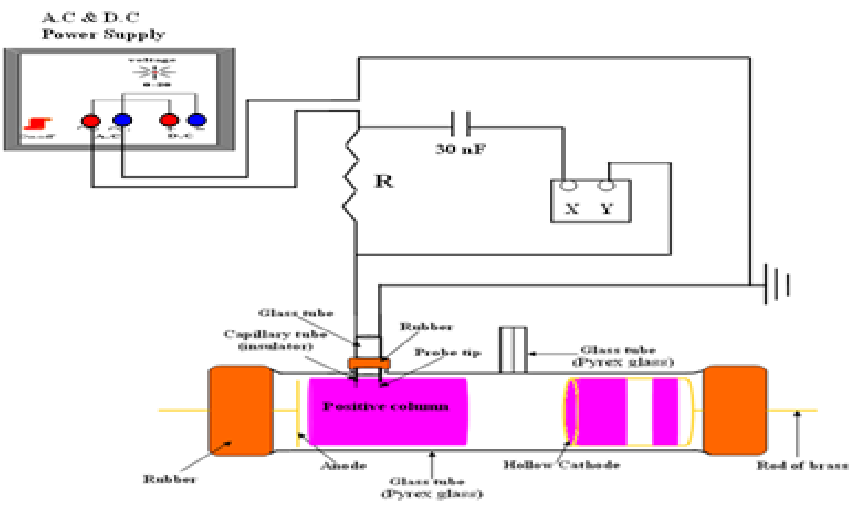

Figure (3) Electrical Circuit of Double Probes

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Determination of the plasma parameters have been done theoretically and practically. In the theoretical part, the parameters have been calculated using relation that holds in the schottky limit depending on the same experimental conditions, such as gas pressure, nature of gas, ionization and discharge radius. In the experiment part, measurements were performed using double probes method. Furthermore a computer program is made to estimate electron temperature and its density from the oscillogram of the double probes

III.1) Theoretical Calculations

The plasma parameters were determined using the relation that electron temperature can be written as an explicit function of the product of gas pressure and radius of discharge in the limit, M.Sato .(1989).

$$eV_i / kT_e = a + b\ln PR \quad (1)$$

where e is the charge, v_i is the ionization potential and for nitrogen equal to 14.5 ev , k is Boltzmann's constant ,T_e electron temperature , R is radius of discharge , p is the gas pressure , a is a constant depends on the type of gas equal to 2.75 for nitrogen and b is a universal constant equal to 2.062 at pR =1 torr cm . Once the electron temperature has been obtained, estimation of the other plasma parameters can be done. The electron temperature as a function of pressure is shown in figure (4). The behavior is close to decreasing exponential, this due to a large mean free path of electron at low pressure and the electron will lose a small energy during collision with others plasma particles S.Yan, H.Kamal, J. Amundson and N.Hershkowitz (1996). The floating and plasma potentials were determined using the following equations.

$$V_f = k_B / e \ln (m_i / M_e)^{1/2} \quad (2)$$

$$V_p = V_f - kT_e / 2e \ln (\pi m_e / 2m_i) \quad (3)$$

The variation of both potentials are nearly decreasing exponential as shown in figures (5 and 6), this attributed to a decreasing Debye shielding with gas pressure D. Akbar (2006).

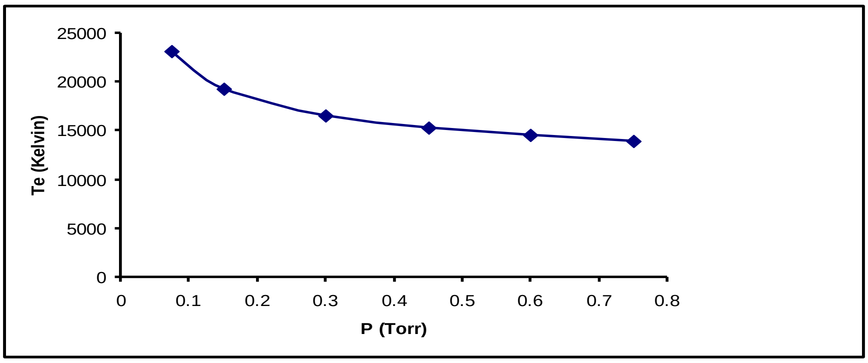

Figure (4) Electron temperature versus pressure theoretically

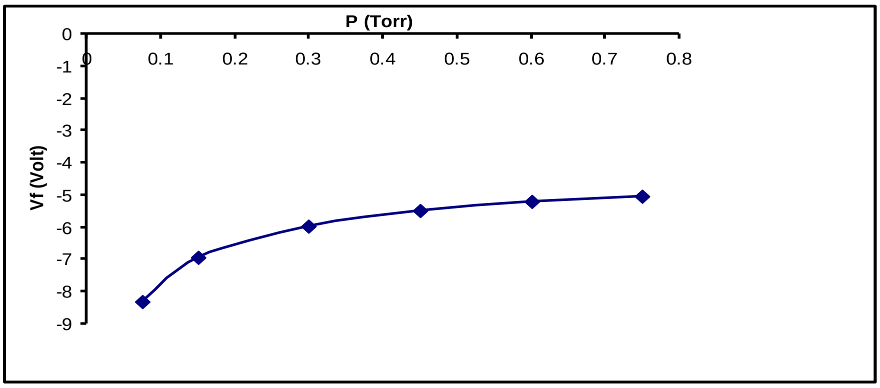

Figure (5) Floating potential versus pressure theoretically

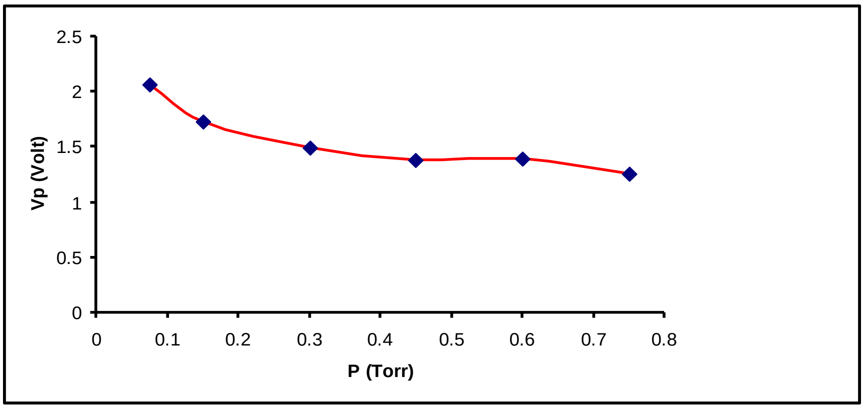

Figure (6) Plasma potential versus pressure theoretically

III.2) Experimental part

The plasma parameters were determined from the double probes characteristics under different conditions of discharge, figure (7) show the double probes characteristics for constant I_d = 1.85mAand radial position r = 0 under different gas pressure.

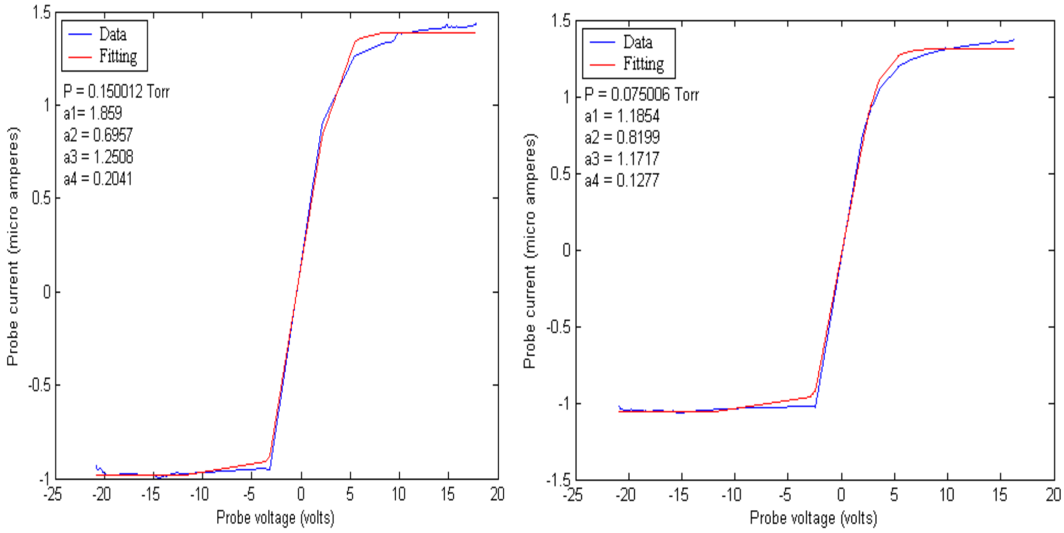

Figure (7) Double probe (I_p-V_p) characteristic at (r = 0 mm) and (I_d = 1.850 mA)

III.3) Pressure Dependence of Plasma Parameters

The electron temperature was determined experimentally for different gas pressure using the following equation

$$\mathbf{I = I_p \tanh (V\text{-}V_o / 2T_{ev}) + I_o} \qquad (4)$$

Where I_o account for any displacement current due time floating potential and the different in stray capacitance to ground for each electrode , T_{ev} is electron temperature in ev , V_o is any constant , which be fixed after getting a good result , I is a small correction to fit this formula to the (I_p - V_p) characteristics which shifted from the original point and I_p is a probe current .Figure (8) show a nearly decreasing exponential relation of both experimental and calculated electron temperature as a function of pressure at the center of discharge . It appears from figure that there is a good agreement between theoretical calculations and experimental measurement. The experimentally measured T_e are less than theoretically calculated , this mean that these values of T_e are reasonable for discharge current more than obtained for current I_d = 1.85mA.

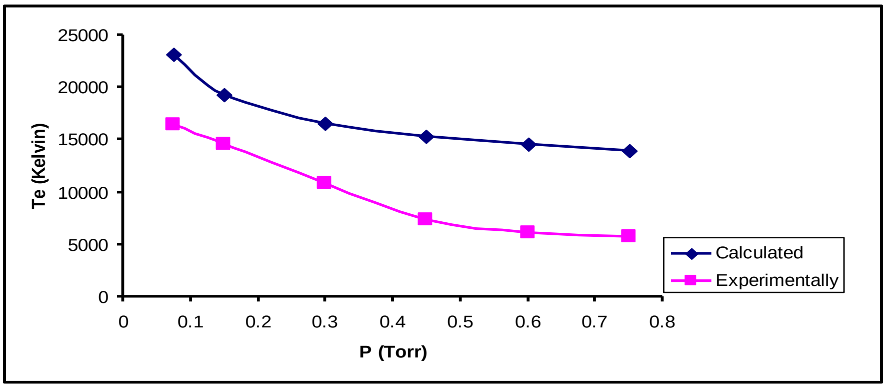

Figure (8) Electron temperature as a function of gas pressure

The floating potential as a function of gas pressure is plotted in figure (9) for both measured and calculated values , the variation is inversely proportional and also close to decreasing exponential function , this behavior is attributed to the total Debye shielding at low pressure and reduced to a partially shielding at high pressure.

The plasma potential V_p is in fact the electric potential in the plasma in the absence of a probe, as well as the potential at which all electron arriving near the probe are collected and the probe current equal to electron current A. Grill (1993).The plasma potential was calculated from equation (3) and compared with those obtained experimentally as shown in figure (10), the variation is inversely proportional and similar to the floating potential. The most important result of the present study is the radial distributions of plasma potential at different constant pressure and discharge current; figure (11), the variation is nearly linear increasing from negative value to positive at the center of discharge toward to the wall. This effect is occurred at the pressure (0.45to 0.75) torr , such change are caused by the accumulation of a heavy negative ions at the axial region of the discharge S. Leshkov et al (2008) and B. Fritschea et al (2008) , however this effect disappear at lower pressure ranged from 0.07 to 0.45) torr for all radial positions .

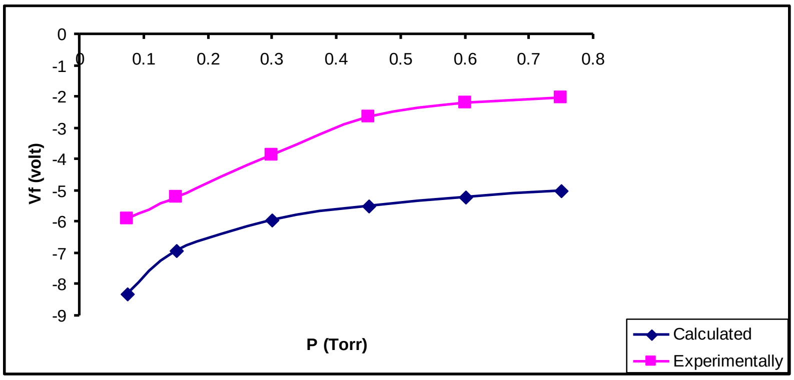

Figure (9) Floating potential as a function of gas pressure

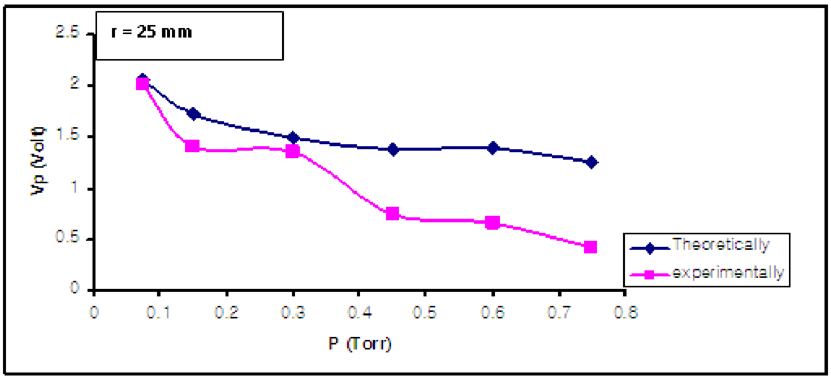

Figure (10) Plasma potential as a function of gas pressure

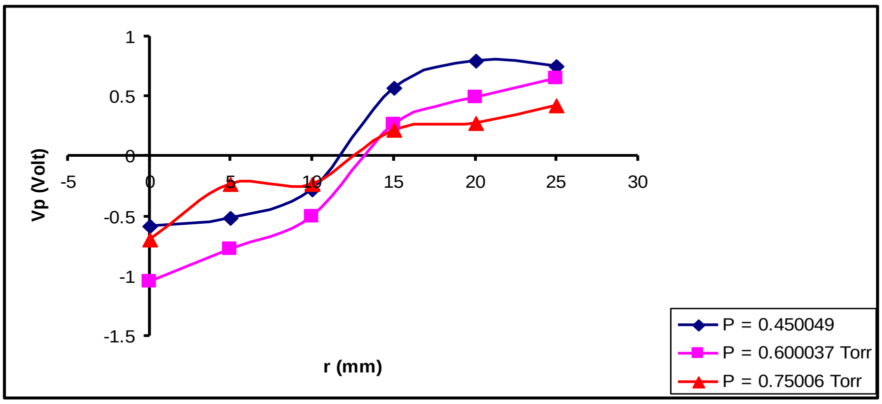

Figure (11) Plasma potential as a function of radial position for (Id= 1.850 mA)

The plasma density is an important parameter in plasma processing because the efficiency of the process occurring in the plasma and their reaction rate are generally dependent directly on the density of plasma A. Grill (1993). The electron density is deduced from the (I_p-V_p) double probes characteristics using the following equation, D. Akbar (2006).

$$\mathbf{I_p = Ane^{3/2}\,(\,T_{ev}\,/\,m_i\,)^{1/2}} \qquad (5)$$

Where A is a probe area, m_i is the nitrogen ion mass and n is the electron density. Another remarkable result of the present study is the radial distributions of electron density for constant current are plotted in figure (12). The relation is the slowly linear increasing from the center toward to the wall due to the specific discharge of hollow cathode. As the pressure increase, fast primary electron emitted by the cathode spend almost energy for excitation and ionization of working gas at distant of several centimeter from the cathode, that is why the plasma density at the axis appear low mostly due to diffusion from the region of its formation, thus maximum of plasma concentration is observed in the region of maximum energy losses of fast electron rather than at the cathode axis, V.Yu. Bazhenov et al. (2001), and V.V. Tsiolko et al. (2009).

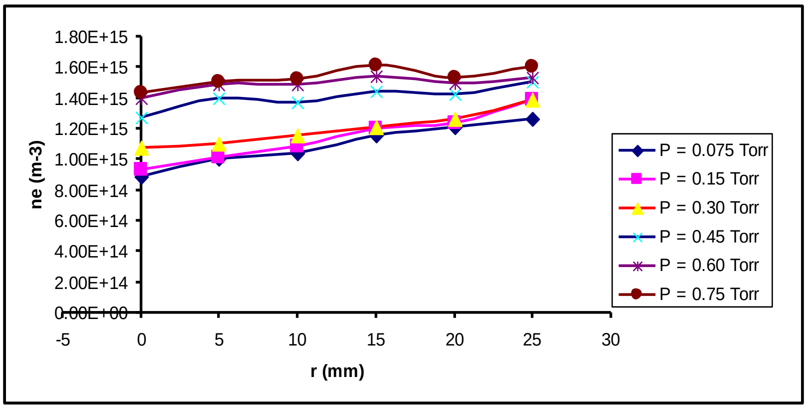

Figure (12) Electron densities as a function of radial position for (Id= 1.850 mA)

IV. CONCLUSIONS

An experimental investigation of hollow cathode nitrogen glow discharge plasma have been made using Langmuir double probes technique , as well as using the relation that holds at Schottky limit to obtain the plasma parameters . The plasma has the density of order 10^{15} m^{-3} and electron temperature in range (400 - 1700). Important conclusions are summarized as follows:

1. The double probes technique has been proven to be very valuable to determine the behavior of plasma parameters.
2. There is a reasonable agreement between the experimentally measured and theoretically calculated of plasma parameters, this in turn have a satisfactory agreement with those from previous studies.
3. The existence of negative values of plasma potential near of the discharge at the pressure (0.45 to 0.75) torr is due to accumulation of heavy negative ions at the axial region of the discharge.
4. The plasma density has minimum at the center of discharge and it grows up slowly along the radius reaching its maximum at the wall, such peculiarly of the distributions is due to the specifics of the discharge with hollow cathode.

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