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Measurement of Low-Pressure Plasma Parameters by the Floating Double Probe Method for Dry Air and Helium Gas in a Capillary Glow Discharge

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Abstract:

The electrical continuous glow discharge is in the capillary tubes. It has gained great interest especially in the applications of liquid crystals as well as display plasmas and soft x-ray lasers. In the present work, an electrical discharge system was designed consisting of a capillary tube and two electrodes. The cathode takes on a hollow geometric shape from nickel material to obtain a high current density. The anode electrode is a tungsten material. The inter-electrodes distance was taken as 12 cm. The floating Langmuir double probe was used as a diagnostic Tool to measure the plasma parameters at different ranges of gas pressure for dry air and helium as working gases. The current-voltage characteristics of the double probe were measured at gas pressure 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 torr. All measurements are conducted at a constant power of 0.6 watt. Electron temperature and ion saturation current were extracted from the I-V characteristics curves. The electron density, Debye length, and plasma frequency were calculated. It was observed that the electron temperature decreases with increasing working gas pressure. The influence of pressure on electron density and ion saturation current gave a clear similarity to the variation in them with pressure in both gases used. Comparisons of the effect of pressure on plasma parameters in working gases were illustrated. The results were in reasonable agreement with previous research.

Keywords: double probe, electron density, electron temperature

قياس معلمات البلازما ذات الضغط المنخفض بواسطة طريقة المجس المزدوج العائم للهواء الجاف وغاز الهليوم في التفريغ التوهجي الشعري

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الخلاصة

تفريغ الوهج الكهربائي المستمر في الأنابيب الشعرية. لقد اكتسب اهتمامًا كبيرًا خاصة في تطبيقات البلورات السائلة بالإضافة إلى عرض البلازما وأشعة الليزر اللينة. في العمل الحالي ، تم تصميم نظام تفريغ كهربائي يتكون من أنبوب شعري وقطبين. يتخذ الكاثود شكلاً هندسيًا مجوفًا من مادة النيكل للحصول على كثافة تيار عالية. القطب الموجب هو مادة التنكستن. تم أخذ المسافة بين الأقطاب الكهربائية على أنها 12 سم. تم استخدام مسبار Langmuir المزدوج كطريقة تشخيصية لقياس معلمات البلازما في نطاقات مختلفة من ضغط الغاز للهواء الجاف والهيليوم كغازات عمل. تم قياس خصائص الجهد الحالي للمسبار المزدوج عند ضغوط 0.2 و 0.3 و 0.4 و 0.5 و 0.6 و 0.7 تور. يتم إجراء جميع القياسات بقوة ثابتة تبلغ 0.6 واط. تم استخراج درجة حرارة الإلكترون وتيار تشبع الأيونات من منحنيات خصائص I-V. بينما تم حساب كثافة الإلكترون وطول ديباي وتردد البلازما. لوحظ أن درجة حرارة الإلكترون تنخفض مع زيادة ضغط غاز العمل. أعطت تأثيرات الضغط على كثافة الإلكترون وتيار تشبع الأيونات تشابهًا واضحًا مع التغير في الضغط في كلا الغازين المستخدمَين. تم توضيح مقارنات تأثير الضغط على معلمات البلازما في غازات العمل. كانت النتائج في اتفاق معقول مع البحث السابق.

الكلمات المفتاحية: المجس المزدوج, كثافة الالكترون, درجة حرارة الالكترون

Introduction

Electrical discharge plasmas comprise of several types, some of them use direct current or alternating current, and others use a high frequency alternating voltage, causing industrial applications to intervene to match them, for example, radio frequency discharge of both capacitively and inductively types [1-5]. Continuous electric discharge has been a good area for research in various laboratory conditions and even in the field of coating and sputtering as well as with capacitive radiofrequency discharge [6]. Hassouba et al. [7] Explain in an experiment by changing the type of electrode material and note that the materials with the lowest work function have the lowest breakdown voltage. They experimentally measured the effect of the electrode material on secondary emission and secondary electrons using rare gases at low pressures [7, 8]. Independent influence of electrode separation in Paschen law, in other words, the Paschen's curve was posted by [9-11]. A theoretical and practical study [12] led to the development of an amendment to Paschen's law. According to the research, the voltage of the electrical breakdown became a function of the pressure setting and the distance between the electrodes of the discharge, as well as a function of the ratio of the distance to the diameter of the electric discharge tube. In most of the studies that were within the continuous electrical discharge, changing the distance between the two electrodes does not come with easy handling [14]. Either it is a micro discharge [15-17] or a discharge by being a long tube with a large diameter [17,18] or what is known as narrow tubes or capillary tubes, which enables the study of electrical discharge and may change the diameter of the discharge tube as well as the possibility of changing the distance between the electrodes [19]. Plasma measurements and diagnoses varied and were of various types to measure the parameters of the plasma, including electron temperature, electron density, Debye length, plasma frequency, etc. [2, 3]. One of these techniques is the use of the Langmuir double probe [19-24], as well as the use of the spectrum emitted from the plasma by using it to calculate the parameters of the plasma [25]. Salman et al. [26] changed the distance between the double probe and studied the effect of this change on the I-V characteristic curve Ghasemi et al.[27] found the electron temperature and electron density practically and in a simulated manner using the Langmuir double probe and they calculated the frequency of the argon plasma which was the highest and the electron temperature in the hydrogen plasma was the highest. The comparison took place between several types of gases. Shrestha et al. [28] haves practically studied the effect of dry air pressure on plasma parameters. Electrical discharge plasma is considered very interesting in capillary tubes because of its many applications as liquid crystal and laser [25] as well as in laser Wakefield acceleration [29] and soft x-ray laser. In the present work, the concern is studying the effect of changing gas pressure in the case of dry air gas and helium as atomic gas as working gases on plasma parameters: electron temperature, ion saturation current, plasma density, Debye length and plasma frequency through the technique of using the Langmuir double probe. Boyle et al. [30] describe and calculate the average temperature of the electrical discharge in hydrogen gas in capillary tubes, where the researchers dealt with the ohmic heating and the heat lost to the walls of the discharge tube in a simulation of a complex system MHD was able to solve the coupled partial differential equation.

Experimental Setup

The discharge system consists of a capillary tube with an inner diameter (3.1 mm) and a length (12 cm) with a distance between the anode and cathode of 12 cm. The anode accessories are contained in a Pyrex glass tube to which the anode is connected and then to the end fixed with the glass to facilitate the connection of high voltages. The length of the anode electrode is equal to (10 cm) connected to an insulated steel cylinder of length (2.5 cm) and diameter (2 cm), then to an insulated copper coil connected on the other side to the terminal through which high voltages are applied, as mentioned above, the diameter of the glass tube that contains the accessories of the anode electrode made of material Tungsten to facilitate a smooth transition of the anode is equal to (3 cm) its length (16.5 cm) as shown in figure (1). From the right side of the electric discharge tube, the hollow cathode electrode from nickel material is used to increase the current density and reduce the striation [2]. The length of the cathode (2.8 cm), the diameter of its inner cavity (0.77 cm)and its outer diameter (0.78 cm) and it is at a distance (8 cm) from the Langmuir double probe. The double probe system consists of two wires of tungsten material, each with a diameter of (0.35 mm) and they penetrate the capillary tube from one side radially to a length (1.9 mm) inside the capillary tube and the distance between them is (1cm). The small part of the probe outside the capillary tube is isolated from each other by capillary tubes of small diameters to avoid any contact between the two probes from the outside. The capillary tube system is vacuumed from the air to a low pressure by using a type of pump Forevac and it reach the pressure to (10^{-2} torr), which is connected to the vacuum system through a high-pressure valve to continue or stop the vacuum without electrical switching off the vacuum pump. The pressure values that were adopted in this experiment are (0.2, 0.3, 0.4, 0.5, 0.6, 0.7 torr). The pressure of the system for electrical discharge is measured using a type of pressure gauge Pirani Edwards equipped with a digital display, as the following pressures were taken in the experiment. Helium gas is injected into the system via a low-pressure valve. The three valves mentioned make up the shape of a T-junction. Each valve performs its function as shown in figure (1). It is worth mentioning for the benefit that the system has been provided with connection points so that each part represents a complete unit that enabled us to control any leakage in the system so that it is examined independently as a single unit. The electrical circuits that are two separate circuits from each other, the first is represented by the electric discharge circuit, which consists of several components and devices. Plasma is generated by a DC power supply 0 to 6000 volts and current 100 mA which supplies voltage across the discharge electrodes up to 6 volts directly from its manufacturer (Leybold- Heraeus). We can also control the electric discharge current through a 10k Ω resistor connected in series with the electric discharge tube, as shown in figure (1). A High voltage was measured directly by voltmeter type Leybold-Heraeus. As for the electrical circuit, which represents another measuring system in addition to the current and voltage of the discharge, it is the circuit of the measurement system for the Langmuir double probes, which in itself consists of the two probes and the voltage applied to the two probes through a variable DC power supply. The voltage source of the Leybold-Heraeus probes circuit can supply voltage from 0 to 300V and a current of 50mA. The probe current is measured by a range-sensing ammeter ($0.1\mu A$), and the voltage is measured by a digital multimeter, as shown in the figure (2) a photograph of the electrical discharge system used to generate both air plasma and helium plasma in the laboratory.

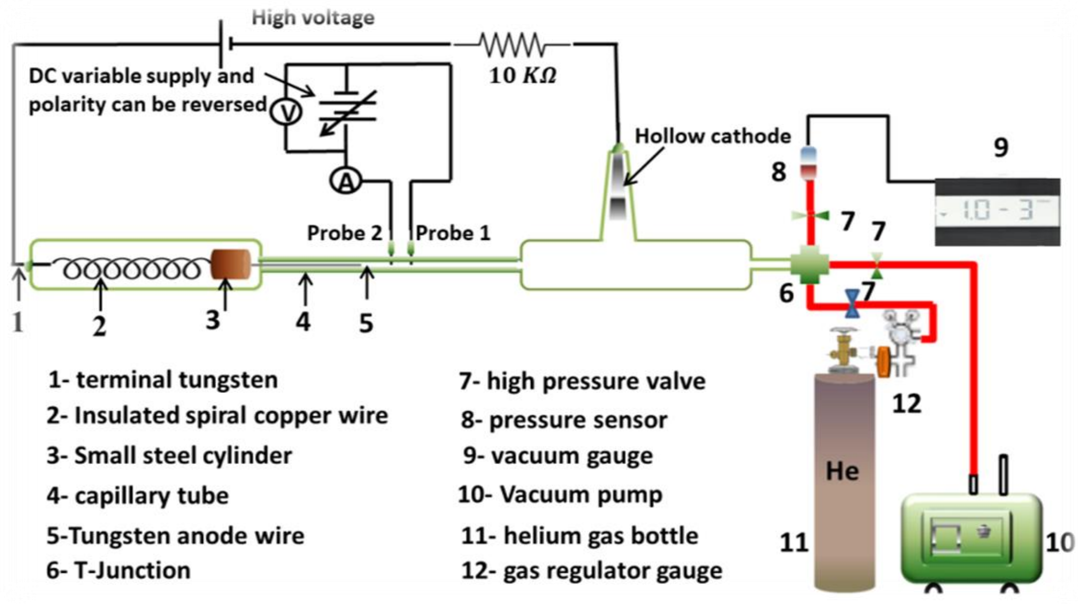

Fig. (1) Schematic diagram of the capillary dc glow discharge system

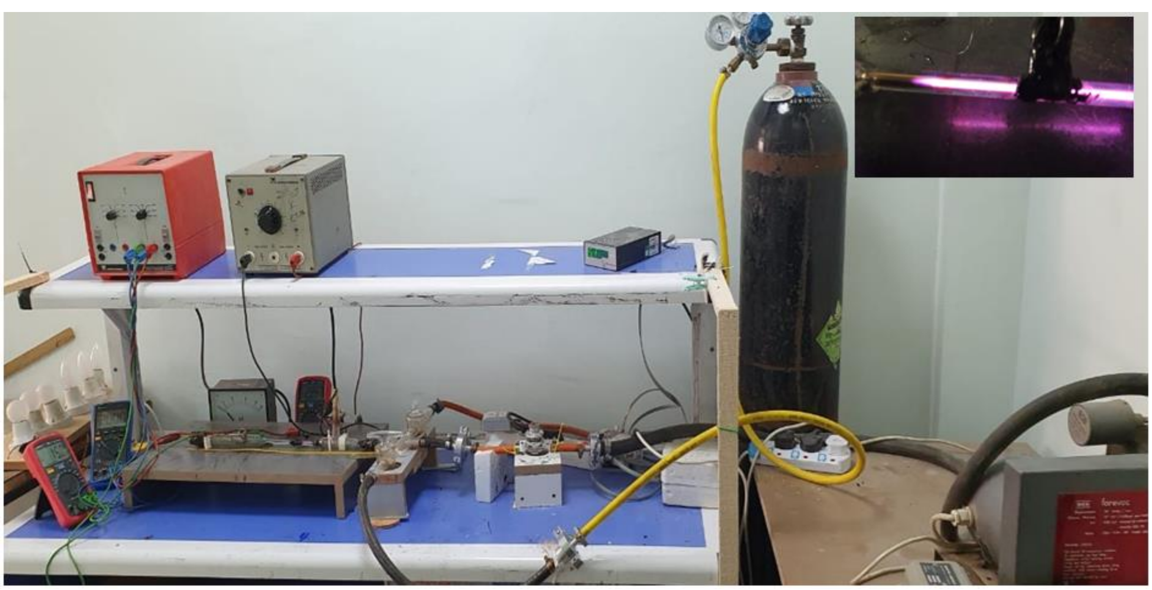

Fig. (2) Photograph of the complete system of continuous capillary glow discharge.

Results and discussion

According to the double probe theory, two electrodes are aligned and arranged so that they form a system with diagnostic technology that eliminates the need for reference [3, 20]. This technique has a distinct characteristic over the use of a single probe in which the least disturbances are created [2], through this system, the calculations of the electron temperature, ion saturation current through the ideal curve of the characteristics curve of the double probe for each of the dry air and helium gas as a working gas at same plasma conditions as a function of gas pressure as in figure (3) and figure (4) respectively.

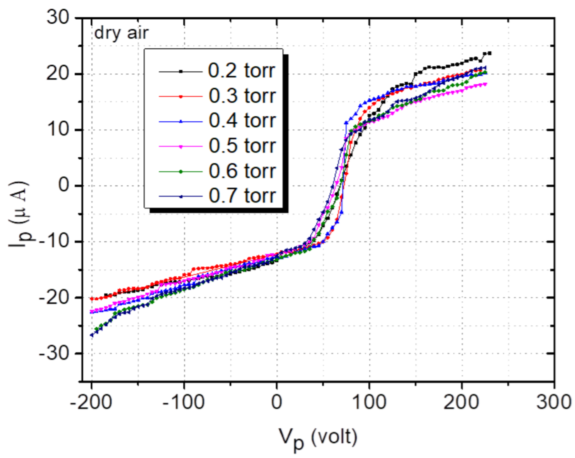

Fig. (3) The I-V characteristics of the double probe for dry air at the inter-electrodes distance is 12 cm and a constant power of 0.6 watt.

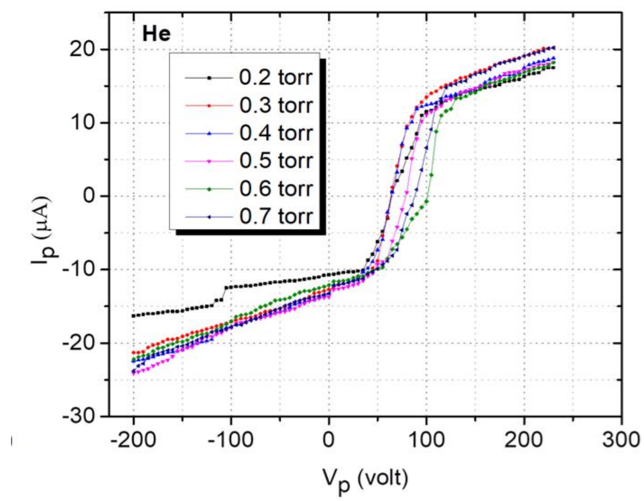

Fig. (4) The I-V characteristics of the double probe for Helium at the inter-electrodes distance is 12 cm and constant power of 0.6 watt.

Plasma positive charge and electrons have a Maxwellian distribution [27]. The I-V characteristics of the floating double probe enable us to obtain the electron temperature from the linear part and the ionic saturation current can also be obtained from the characteristics curve, which represents the important parameters that lead to the plasma density values, as in the following equation [31]:

$$I_{sat} = 0.6An_e\sqrt{\frac{KT_e}{m_i}} \quad \text{..........} (1)$$

Where m_i, n_e, and T_e, K, A are representing the ion mass, electron density, electron temperature, Boltzmann constant and probe surface area. Figure (5) gives us the relationship between electron temperature and pressure change. Figure (3) and figure (4) give the current and voltage characteristics in the case of the double probe, the electron temperature can be obtained from the slope of the curves so that the value of the electron temperature is directly obtained [20, 21]. Figure (5) shows that there is a decrease in the Electron temperature with a variation of pressure towards its increase, the result agrees with [28,32]. The process of multiplication electrons in the plasma with the continuation of their generation, and the transformation of the plasma is self-sustaining, leading to the continuation of successful collisions with the availability of sufficient energy for the electron to ionize the neutral atoms These processes lead to a decrease in the electron temperature or the collision of electrons with the container glass. Perhaps because the density of helium is less than the density of air, which is an intuitive information between the two gases and here: a difference in masses because helium gas is an atomic gas while air is a molecular gas, and this mass difference allows helium atoms to move easily, which gives a probability for the electron to retain its energy with few inelastic collision chances. The slower movement of the molecules gives and the greater the mass gives opportunities for collision. The molecules of air need dissociation, then the second stage comes the process of ionization by inelastic collision, so the electrons gave a lot of their energy, and thus the electron temperature decreases within this sequential scenario with respect to air [28,32]. In any case, what happens with air as a working gas differs from what is the case in the rare atomic helium gas. In practical and theoretical research, it was proved that the electron temperature in helium is higher than in air [27].

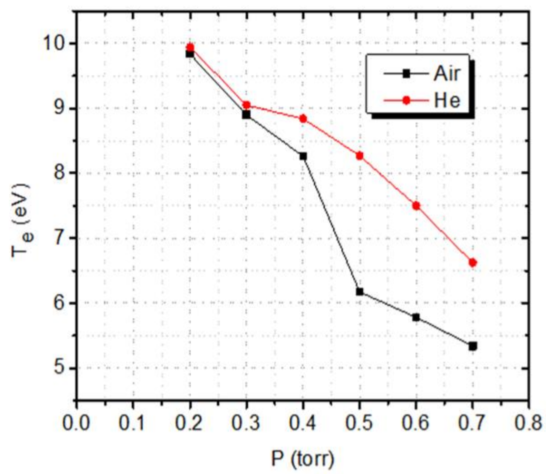

Fig.(5) shows the variation of electron temperature with the gas pressure at an inter-electrode distance is 12 cm and the power is constant 0 .6 watt for dry air and helium gases.

Figure (6) shows electron density versus gas pressure the range of change of the electron density with the pressures that were chosen for dry air and helium gas at the distance between the electrodes 12 cm and a constant power of 0.6 watt, which is beyond doubt and by looking at that relationship it appears that the electron density increases with the increase in pressure, it is the same as the case of the ionic saturation current, which shows a change with the pressure of the gas in figure (7). The electron density also increases with increasing pressure. The increase in secondary electrons after the electrical breakdown comes from several sources, either the collision of electrons with neutral atoms and their ionization, or from the collision of ions with the cathode, or sometimes resulting from photo-ionization. Usually, it is more likely to occur in narrow tubes and capillary tubes [2, 4]. The production process here overcomes the process of the recombination process. The relationship of saturation current and electron density with pressure which shown in figure (6) and figure (7) takes its somewhat systematic form, also reveals that ion saturation current is calculated from the current and voltage curve of the dual probe for each pressure value [20, 27]. The saturation ionic current and electron temperature are considered important indicators of the change in the electron density in the plasma. Figure (6) clearly shows the decrease in the electron density in helium plasma compared to dry air plasma, where this result agrees with the practical and theoretical results in [27]. We also note the decrease in the electron density after reaching a maximum value and at a pressure of 0.5 torr and 0.6 too for both helium and air plasmas, respectively. The process may be due to recombination to form neutral atoms. This result is consistent with [27, 28]. It applies to the saturated ionic current relation with pressure.

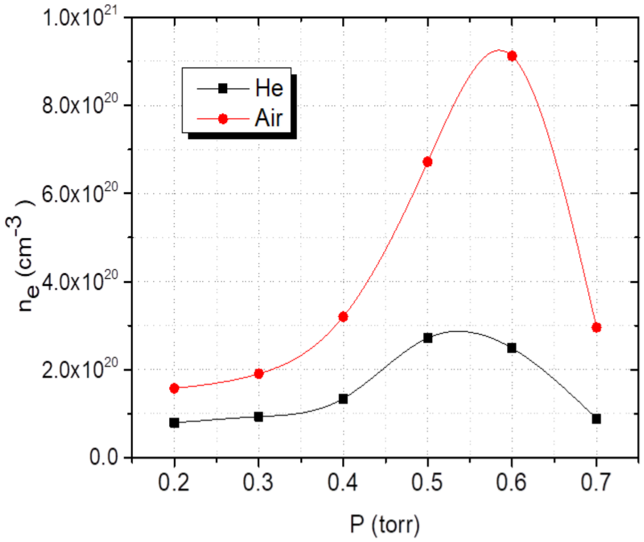

Fig. (6) shows the range of change of the electron density with the pressures that were chosen for dry air and helium gas at the distance between the electrodes 12 cm and constant power of 0.6 watt.

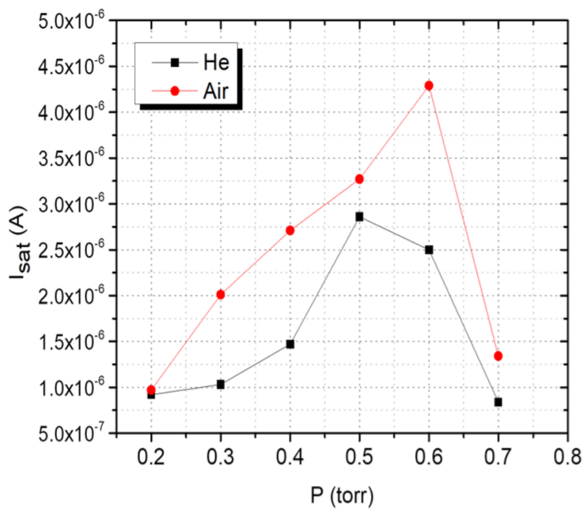

Fig. (7) The variation of the ionic current saturation with the working gas pressures at the distance between the electrodes 12 cm and a constant power of 0.6 watt

It is possible to make a note that a charged particle will be shielded by the plasma from regions and critics that are located at distances greater than the Debye length, on this basis, the Debye length represents the distance by which the electric field generated by the separation of positive and negative charges is equalized [3,33]. The Debye length is given by the following formula [3]:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 K T_e}{n_e e^2}} \qquad (2)$$

Figure (8) gives the Debye length as a function of the working gas pressure at the space between the electrodes 12 cm and constant power of 0.6 watt. It is noticeable that there is a decrease in the Debye length with the increase in pressure, meaning with the increase in the number and concentration of ions, this leads to the Debye length being thinner with the increase in pressure this result agrees with [28]. After the pressure 0.5 and 0.6 torr for helium and air respectively, the Debye length starts to increase slightly, this is due to the state. As the pressure increases, the concentration of molecules or atoms increases, leading to an increase in entropy and thus the shielding cloud will spread. As the number of molecules or atoms increases, the temperature rises slightly, which leads to an increase in the Debye dimension. Also, figure (8) shows that the Debye length in helium is greater than the Debye length in the air at the same conditions because the electron temperature is higher in the case of helium as in figure (8) and as in equation (2). Which is mentioned in the phrase mentioned above, which is that the distribution of the types of charged particles, by which we mean positive ions and electrons, which collect at the sheath of the plasma wall near the probe, that is the primary sheath, is of a Maxwellian distribution, and there are successful transitions between the primary sheath and the sheath, so the electrons and ions that succeed in reaching penetrating the sheath are which had a high thermal velocity. It is obvious that the calculation of plasma frequency directly depends on the density of the plasma. The electronic cloud fluctuates relative to the ionic cloud, and it is calculated by the following formula[2]:

$$f_p = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \ldots\ldots (3)$$

Figure (9) gives the change of plasma frequency with gas pressure for a distance of 12 cm for both dry air and helium. The behavior of the variation is similar to that of plasma density with pressure which revealed plasma density with pressure change [28]. Also, the plasma frequency in dry air plasma is greater than in helium plasma [27].

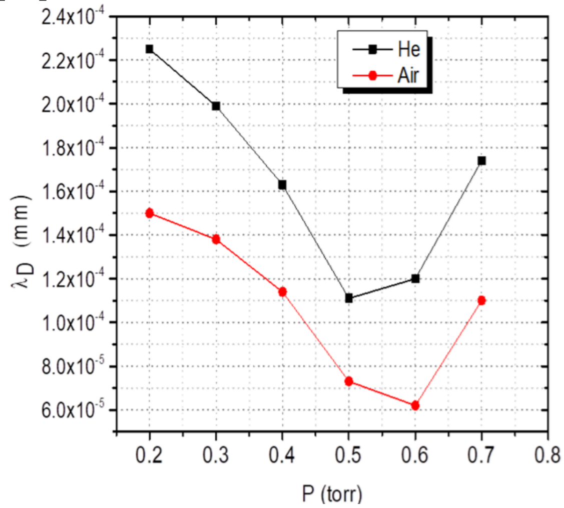

Fig. (8) The change in Debye length with the change of pressure for dry air and helium as working gases at inter-electrodes distance equal 12 cm and constant discharge power of 0.6 watt.

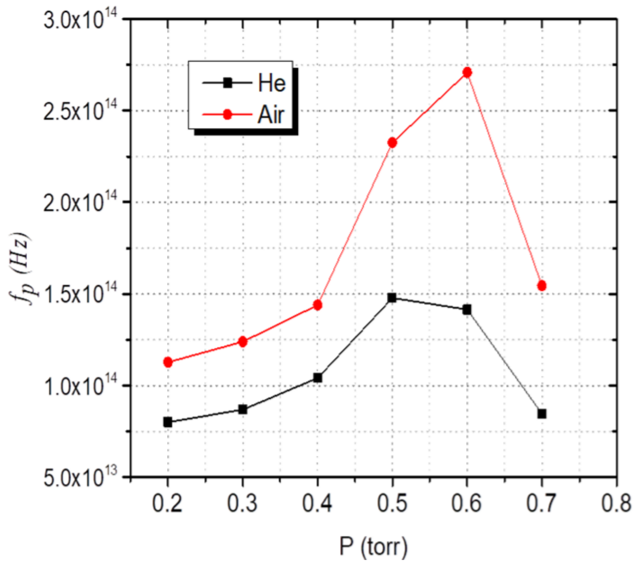

Fig. (9) The change in plasma frequency as a function pressure for dry air and helium as working gases at inter-electrodes distance equal 12 cm and constant discharge power of 0.6 watt.

Conclusions

Through the continuous electrical glow discharge in the capillary tubes in dry air plasma and helium plasma, we can conclude the following:

- The current and voltage characteristics curve of the floating double probe gave the ability to calculate the ion saturation current and electron temperature.
- The temperature of the electron decreases for both working gases with increasing pressure, and this result is in agreement with previous results [28, 32].
- Electron temperature in helium plasma is higher than in air, and the result is agreed [27].
- The electron density has a regular shape that falls at pressures 0 5 and 0 6 torr for helium gas and dry air, respectively and this result is in agreement with previous results [28].
- The electron density in helium plasma is higher than in dry air plasma and the plasma frequency in dry air plasma is greater than in helium plasma these results are in agreement with previous results [27].

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