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Plasma Properties of a Low-Pressure Hollow Cathode DC Discharge

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Abstract

The current study involves an experimental investigation of plasma main parameters of a DC discharge with a hollow cathode (HCD) geometry in air using apertures of different diameters from the hollow cathode (1, 1.5, 2, and 2.5 cm). A tiny Langmuir probe is used to investigate the plasma properties. The HCD was operated at constant power of 12.4 W and gas pressures ranging between 0.1 to 0.8 torr. It was observed that the operational conditions strongly affect the electron temperature and density, while the hollow cathode diameter has not much influence. The main important observation was that at relatively high air pressure (>0.4 torr) two electron temperatures were obtained, while at relatively low pressure (<0.4 torr), a single electron temperature was found. The results showed that the measured electron temperature decreased nearly linearly with increasing gas pressure.

Keywords: Hollow cathode discharge, Langmuir probe, electron temperature

خصائص بلازما الضغط الواطئ للكاثود المجوف في منظومة التفريغ المستمر

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الخلاصة

تضمنت الدراسة الحالية التحقق عمليا في المعلمات الرئيسية للبلازما لتفريغ التيار المستمر بالهواء باستخدام الكاثود ذو الشكل الهندسي المجوف (HCD) باستخدام فتحات مختلفة من تجويف الكاثود باقطار (1 ، 1.5 ، 2 ، 2.5 سم). تم استخدام مجس لانكمور الصغير لفحص خصائص البلازما. تم تشغيل التفريغ للكاثود المجوف بقدرة ثابتة تبلغ 12.4 واط ومدى ضغط الغاز من 0.1 إلى 0.8 تور. وقد لوحظ أن ظروف التشغيل تؤثر بشدة على درجة حرارة الإلكترون وكثافته بينما قطر الكاثود المجوف ليس له تأثير كبير على قيمه. الملاحظة المهمة الرئيسية هي أنه عند ضغط هواء مرتفع نسبيًا (> 0.4 تور) تم الحصول على درجتي حرارة للإلكترون بينما عند ضغط منخفض نسبي (<0.4 تور) تم العثور على درجة حرارة إلكترون واحدة. أظهرت النتائج أن درجة حرارة الإلكترون المقاسة تنخفض بشكل خطي تقريبًا مع زيادة ضغط الغاز.

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Introduction

In plasma production systems, replacing the planar cathode with a hollow structure resulting from the negative glow moves inside the hollow cathode [1]. As a result, most of the discharge occurs inside the cathode causing additional excitation and ionization processes via oscillating electrons. This is called the hollow cathode effect and it produces a higher current density and more intense plasma emission than the planar discharge [2-4]. The hollow-cathode discharges (HCDs) are crucial in many applications being the cornerstone in their work as in the production of intense particle beams, thin film coating of surfaces via plasma sputtering, UV generation devices, and plasma switches [5-8]. A balance is required among the different variables of the particular HCDs applications, for example, electrode shape, inter-electrode distance, high voltage applied (discharge voltage applied), aspect ratio, and the best features of discharge pressure magnetic field [9]. A variable count of hollow-cathode geometries as a hollow cylinder (one side or both sides opened), two parallel plates, and maybe spiral configuration [6]. Restraint of electrons in the cathode cavity is behind the influence of the hollow-cathode that appears as a sudden decline in the discharge operating voltage with an elevation of the discharge current [10]. Many researches have been done on the hollow cathode influence on the plasma parameters using single Langmuir probe or double probe techniques; this topic still attracts researchers to experimentally investigate the effect of hollow cathode diameter and depth on the plasma parameters[11,12]. Two slow electron groups have been described in the negative glow of the hollow cathode discharge using the Langmuir probes. The slowest group (named final electrons) located in the hollow cathode potential well forming the plasma concentration portrait showing the Maxwellian distribution with a temperature of less than 1 eV. The other group is constituted of the secondary electrons showing energy of about 3 eV. The results from the ionization at the cathode sheath unique end lead to the transmission of the electrons to the anode [13]. Honglertkongsakul and Ngamrungroj studied the effect of gas pressure on electron temperature in nitrogen plasma. Their results showed an increment in the plasma column with an elevation of the nitrogen pressure while the electron temperature did not exceed 0.8 eV [14].

In the current work, some plasma characteristics in the HCD system with an adjustable diameter of the hollow cathode aperture were investigated. Langmuir single probe was used as a diagnostic tool to determine the plasma parameters. Gas pressure, electron temperature, and plasma density were also measured.

Experimental Setup

The experimental setup is shown in Figure 1. The figure shows the electrical discharge system, the equivalent electrical circuit of the electrical discharge system (schematics of Langmuir probe electric circuit in a hollow cathode discharge system), the hollow cathode electrode and the disc-shaped anode electrode of different diameters. Figure 1a shows the Pyrex glass discharge tube of 20 cm length and 3.4 cm inner diameter. Two brass electrodes are fixed in the discharge tube. The distance between the two electrodes (electrodes separation) is 12 cm. The cathode (the hollow cathode) has a cylindrical shape with a cavity depth of about 1 cm. The other side of the cathode was connected to a DC high voltage power supply (HVPS) via a screw. The cavity diameters of the used hollow cathode are 1, 1.5, 2, 2.5 cm. The hollow cathode outer surface with the rim was insulated by a solid Teflon cylinder prepared by lathe in a way that the brass fitted into the machined region. On the other hand, the anode disk was insulated from the side away from the discharge. The used anode diameters are 1, 1.5, 2, 2.5 cm. These diameters matched the cavity diameters (to ensure a uniform field).

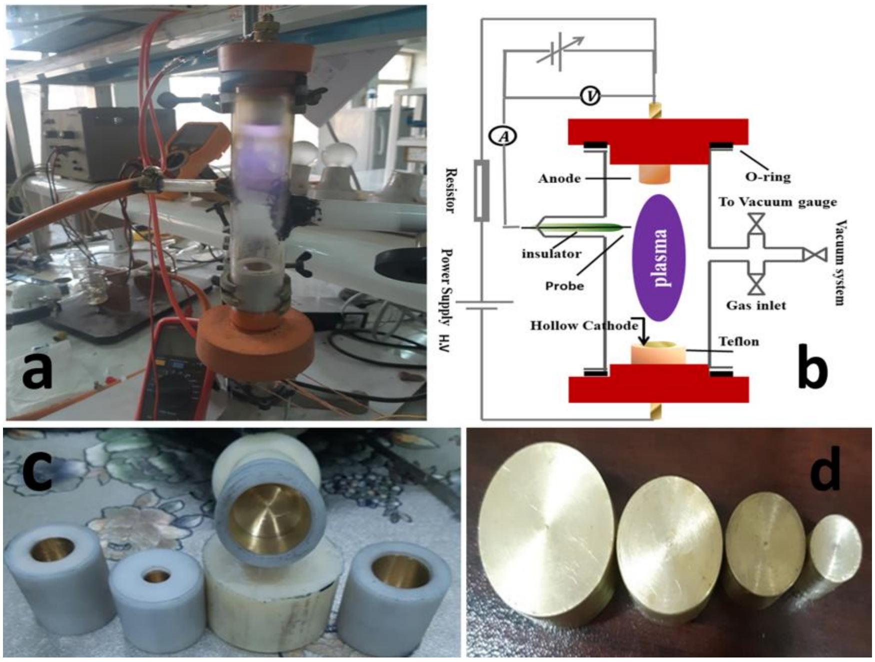

Figure 1- **a**: The electrical discharge system, **b**: the equivalent electrical circuit of the electrical discharge system and the diagnostics method, **c**: the hollow cathode electrodes, **d**: disc-shaped anode electrodes of different diameters

The discharge tube is connected to T-junction Pyrex high vacuum valves. Each valve performs a certain function. The first valve of the T triple junctions was connected to the vacuum pump via a rubber high vacuum tube. The second valve was connected to the gas inlet tube. The last one was connected to the vacuum gauge. The used vacuum system was the NGN Forevac rotary pump (ultimate vacuum$10^{-2} torr$). The minimum base pressure reached was 0.13 torr. The pressure was measured with Edwards Active Digital Controller connected to Edwards Pirani WRG-S Active Wide Range Gauge KF25 Flange. The applied high voltage was measured with a high tension probe-type tesla model BS375A. The discharge current was calculated by measuring the applied voltage across 1.2 k Ω resistance connected in series with the anode. A movable Langmuir single probe was fixed at 4 cm from the anode. It consists of a glass sheath covering a 7 cm tungsten wire leaving a small tip cylinder, which is in touch with the plasma. The probe is cylindrical shaped with a diameter and length of 1 mm and 3 mm, respectively. One side of the probe was connected to a soft iron slug connected to a spiral isolated coil linked to the tungsten terminal. The Langmuir probe is biased from Lybold DC power supply 0-300 volt and 0-25 mA. A homemade high voltage power supply is used to produce the discharge. This high voltage power supply has a variable range between 0 and 2500 volt, and the maximum provided current is ~ 1 A.

The diagnostic method of Langmuir probe was used to measure T_e, which was presumed to follow the Maxwellian distribution. As shown in equation (1), T_e, depends on the variation of the logarithm of I_e to the applied probe voltage (V) [15]:

$$\frac{d}{dV} In\, I_e = \frac{e}{kT_e} \quad (1)$$

Where e and k are the elementary charge and Boltzmann’s constant, respectively. Because the efficiency of plasma processes and their reaction rates are generally directly dependent on the density of charged particles, electron density is an important parameter in plasma processing. The electron density can be determined from the relation between the electron saturation current I_{es} and the electron temperature as given [16]:

$$I_{es} = n_e e A_p \sqrt{\frac{kT_e}{2\pi m_e}} \qquad (2)$$

Where: ne, Ap, e, and me are the electron density, the probe surface area, the electric charge and electron mass, respectively. The point of plasma potential, Vp is the point which corresponds to the electron saturation current. The density of electrons is determined from Equation (2) by using the value of Te.

Result and Discussions

The effects of the gas pressure on the electron temperature and density were investigated with a single Langmuir probe. To obtain the I-V characteristic curve of the probe, the probe biasing voltage was varied from −150 to +150 V. Figure 2 shows the I–V curves for the air discharge for 2 cm hollow cathode diameter at different gas pressure and constant discharge power of 12.4 W. It can be seen that the I–V characteristic curves of the Langmuir single probe obtained illustrate a typical well-known behavior. The probe current exhibited a sharp growth over the applied bias voltage for all the working air pressure range. This significant variation in discharge current corresponds to measurements reported in a previous study [17]. The measured probe current I_p in Langmuir probe technique is comprised of I_i, the ion current, and I_e, the electron current. Therefore, it is essential to subtract I_i from I_p to determine I_e. The tangential line in the large negative bias voltage range is considered as I_i, as shown in Figure 2; then $I_e = I_p - I_i$, but in the present case, I_i was very small compared to $I_{p;}$ therefore, it was considered that $I_e \approx I_p$. The analysis of Langmuir characteristics curves according to the typical formula described in literature gives the values of electron temperature T_e.

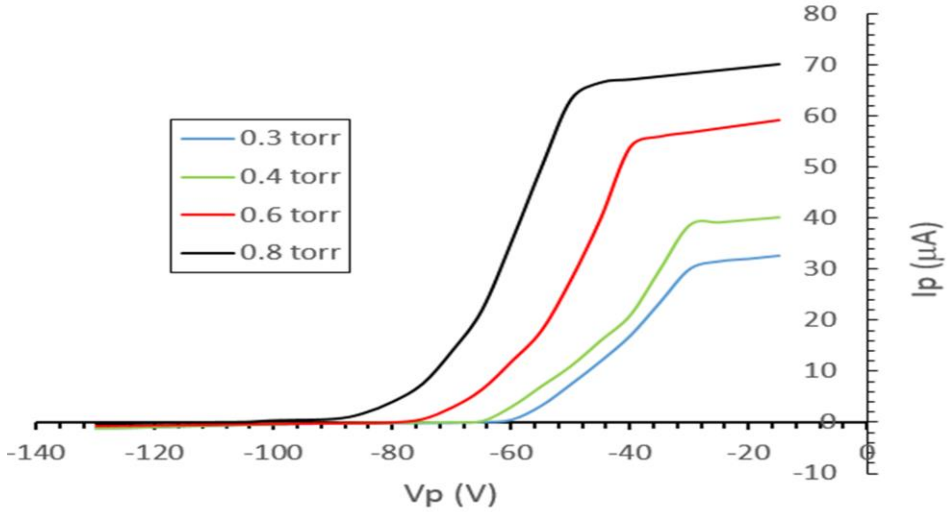

Figure 2- Langmuir probe current as a function of the probe bias voltage at 2 cm hollow cathode-type discharge.

Figure 3 illustrates the semi-log plot of I_p versus V_p at a pressure of 0.8torr. It can be seen that there are two values for electron temperature corresponding to T_{e1} = 12.1 eV for the bulk electrons and T_{e2} = 7.8 eV for the tail electrons. This structure is explained as follows: the relatively high electron temperature is caused by the ionization mechanism inside the hollow cathode. Ionization occurs via two mechanisms: volume ionization and photo-ionization. Volume ionization is caused by electrons swinging from one side of the hollow cathode to the other like a "pendulum" and gaining energy in the cathode fall region, whereas photo-ionization is caused by intense radiation inside the hollow cathode. On the other hand, the relatively low electron temperature comes from background plasma enhancement when the hollow cathode discharge has not yet been burned inside the cathode. This result agrees with that obtained by Sato et al.[18]. They measured the electron temperature in a hollow cathode discharge using different floating probe techniques.

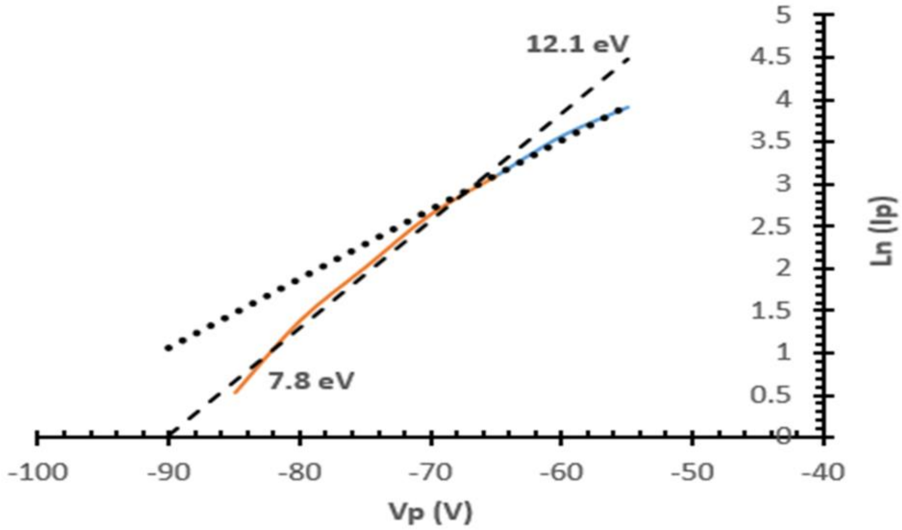

Figure 3- Semi-log plot of I_p versus V_p at a pressure of 0.8 torr.

The effect of the gas pressure on the electron temperature (the tail and the bulk electrons) is shown in Figure 4. In general, it can be observed that the electron temperature decreased with increasing gas pressure due to the cooling effect in the plasma [17]. It is worthy to observe that at relatively low pressures (≤ 0.4 torr), the measurements show that the tail and the bulk electrons have the same temperature. While at pressures (>0.4 torr), the two values of the electron temperature are distinctively different. The impact of gas pressure variation on discharge properties is expected because increasing the pressure increases electron collisions with the plasma species, thus enhancing the hollow cathode effects [19].

Figure 5 depicts the variation of the density of electrons with the gas pressure. It is seen that the electron density behavior with gas pressure is opposite to that of electron temperature. The electron density increases with increasing gas pressure. This behavior can be ascribed to the fact that as gas pressure increases, the electron-collision frequency with gas atoms and molecules increases and in turn, the mean free path between successive collisions decreases [19]. As a result, an increasing amount of energy is transferred from the electrons to the plasma species rather than the electrons gaining energy. In this case, the balance between total ionization events and total particle losses to the chamber walls decreases. And the difference between total ionization events and the total particle losses to the chamber walls decreases the electron temperature and increases the electron density.

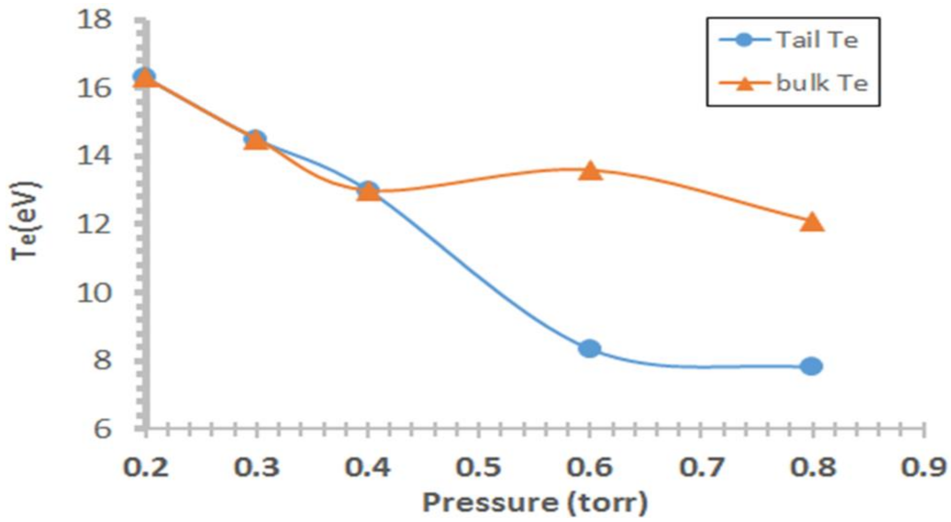

Figure 4: Electron temperature, T_e, as a function of air pressure at 2 cm hollow cathode-type discharge.

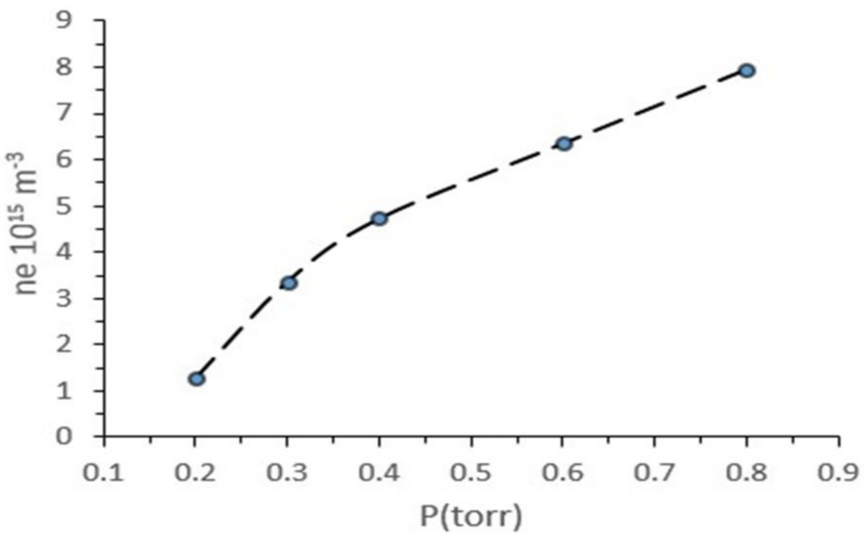

Figure 5- The density of electrons, n_e, as a function of air pressure at 2 cm hollow cathode-type discharge.

The effect of the hollow cathode diameter on the electron temperature and electron density was investigated at constant discharge power (12.4 W) and gas pressure (0.3torr). The measurements showed that the values of the electron temperature and electron density are almost independent of the diameter of the hollow cathode, as shown in Figure 6. These results agree with those of Bhuyan et al. [13]. At a relatively high power with discharge operation conditions similar to those used in the present work, the discharge process gradually moves into the cavity of the hollow cathode electrode forming a virtual anode potential that yields a much higher electron density than that of a discharge outside the hollow cavity. As a result, the diameter variation does not strongly affect the plasma parameters far from the electrode [10].

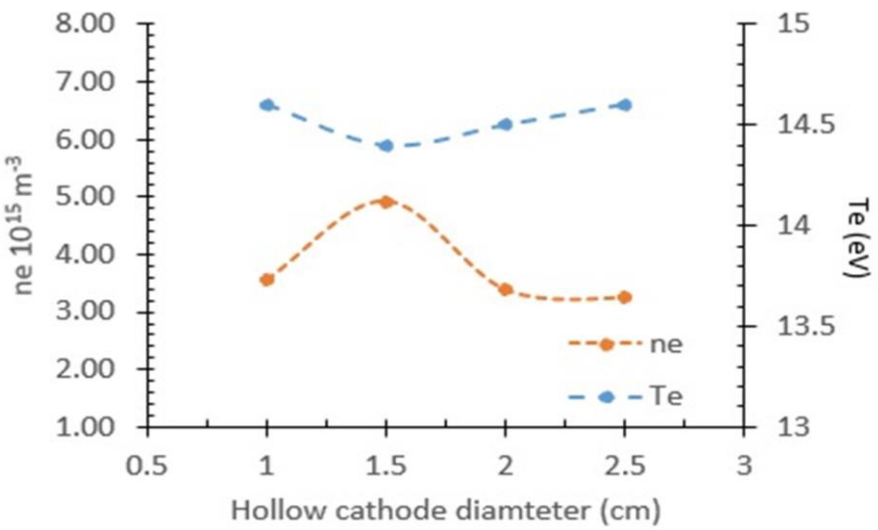

Figure 6- Electron density, n_e, and electron temperature as a function of hollow cathode diameter at 0.3torr gas pressure and discharge power of 12.4 Watt.

Conclusions

In the present work, the electron temperature and the electron density in a hollow cathode DC glow discharge were experimentally measured with a Langmuir single probe at constant discharge power. The probe measurements revealed that the two groups of electron temperature characterized the plasma at a gas pressure range above 0.4torr. As the gas pressure increased, the electron temperature decreased and hence an increase in the electron density was obtained. At a relatively low-pressure regime (i.e., P=0.3torr), the change in the diameter of the hollow cathode did not distinctly affect the electron temperature and hence the electron density at constant discharge power.

Acknowledgement

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