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Computational Study of DC Glow Discharge and the Effect of Voltage on the Parameters of the Resulting Plasma

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Abstract

Recently, the computational procedure has become the best and low-cost tool for various studies, both theoretically and practically, due to its ability to process huge data in a short time. In this research, a computer study was conducted in two dimensions of the DC glow discharge, where a noble reactive gas, argon gas was used to study the effect of voltage on the parameters of the resulting plasma. The particle flow was approximated using the diffusion approximation based on the fluid model, excited and neutral types where it was found that the density of electrons, the temperature of the electrons, the electric potential, and the density of ions will increase with the increase of the applied voltage.

Keywords: Plasma Physics, COMSOL Multiphysics, Simulation.

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Introduction

Over the past few years, plasmas have been used in numerous significant applications, including those involving glasses [1], magnetic media, thin film materials, semiconductor fabrication, etc[2,3]. Glow discharge (GD) is plasma with an ionized gas that includes neutral species as well as more positive or negative ions. Different potentials have been applied between two electrodes to create such systems[4]. Glow discharge plasma is a low-temperature region of gas that is maintained by the strong electrons. Consider two electrodes inside a chamber containing gas, the glow that will be formed in low temperature gas with a high-impedance DC[7]. The produced plasma is in the abnormal glow discharge[5,6]. In this study, aluminum was used as electrode target and the properties of argon plasma generated by electrostatic discharge were studied [8]. In order to determine plasma parameters such as electron temperature (T_e), electron number density (n_e), Debye length (λ_D), plasma frequency (ω_p), and ion density (n_i) by performing a two-dimensional simulation using the Comsol program and for different voltage values.

Model of DC Glow Discharge Plasma

The mathematical explanation for the DC light discharge is the Poisson equation, which displays a balance of particle density (electrons and positive ions). As demonstrated below, drift equations are solved to get electron density and energy [9].

$$-\nabla.\epsilon_0\epsilon_r\nabla V = \rho \ (1)$$

$$\frac{\partial(n_e)}{\partial t} + \nabla.[-n_e(\mu e.E) - De.\nabla ne] = Re \ (2)$$

$$\frac{\partial(n_\varepsilon)}{\partial t} + \nabla.[-n_\varepsilon(\mu_\varepsilon.E) - D_\varepsilon.\nabla n_\varepsilon] + (E.\Gamma_\varepsilon) = R_\varepsilon \ (3)$$

$$\Gamma_\varepsilon = -n_e(\mu e.E) - De.\nabla ne \ (4)$$

The energy loss R_ε, from elastic collisions and the R_e electron source will be specified. The formulae below will be used to compute electron and energy diffusion, as well as energy mobility.

$$D_\varepsilon = \mu e\, T_e\,,\ \mu_\varepsilon = \left(\frac{5}{3}\right)\mu e, D_\varepsilon = \mu_\varepsilon T_e \ (5)$$

Source coefficients in equations using plasma chemistry where we assume that (M) is the number of interactions that are involved in some neutral inelastic collisions (P) where in general P >> M. The source of the electron according to rate coefficients is obtained through the following relationship.

$$Re = \sum_{(j=1)}^{(M)} X_j\, K_j N_n n_e \ (6)$$

xj The mole fraction of the target species in reaction j, k_j is the reaction j rate coefficient (m^3/s), and (N_n) overall neutral number density ($1/m^3$). When defining reaction rates, it is preferable to utilize Townsend coefficients rather than rate coefficients. We can better explain the events in the cathode subsidence region using Townsend coefficients, the electron source is given.

$$R_e = \sum_{j=1}^{M} X_j\, \alpha_j N_n |\Gamma_e| \ (7)$$

Town send's coefficient is (αj). The Townsend coefficients improve the stability of numerical calculations. The summation of collision-related energy loss in the reaction leads to the loss of electron energy.

$$R_\varepsilon = \sum_{j=1}^{P} X_j\, K_j N_n n_e \Delta\varepsilon_j \ (8)$$

Where $\Delta\varepsilon_j$ is the amount of energy lost in reaction j. Using the cross-section data and the following integral, the rate coefficients are calculated.

The mass fraction of each non-electronic type is calculated using,

$$\rho = q\int_{\infty}^{0} \varepsilon\, \sigma_k(\varepsilon) f(\varepsilon) d\varepsilon \ (9)$$

$$R_\varepsilon = \sum_{j=1}^{P} X_j\, K_j \alpha_j N_n |\Gamma_e| \Delta_{\varepsilon j} \ (10)$$

The equation determines the mass fraction of each non-electron species:

$$\rho = \frac{\partial}{\partial t} w_k - \rho(u.\nabla)w_k = \nabla.j_k + R_k \ (11)$$

To calculate the density of space charge, plasma chemistry is used in this model [9].

$$\rho = q\sum_{K=1}^{N} Z_j n_k - n_e \ (12)$$

Geometry and Mesh

This work is a simulation of a DC glow discharge in a two-dimensional system of planar electrodes as shown in the figure, placed inside 40 cm long discharge system as in figure 1 under the influence of a pressure of 0.6 torr and different voltage values (125V, 145V, 165V and 185V). This enabled us to reduce time and effort during the simulation, where the finite element method was used to solve the proposed model. The solution area is the distance between the negative electrode and the positive electrode where the network elements have simply been applied along this distance. The majority of important events fall within this range.

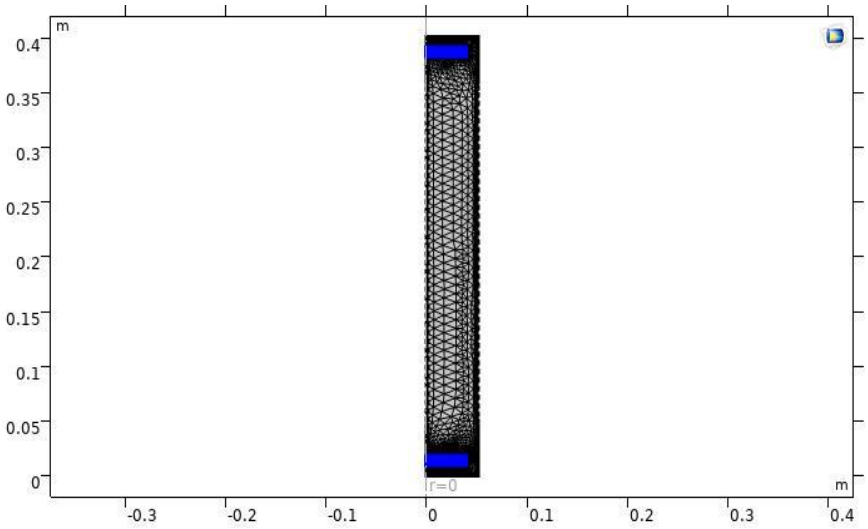


Figure 1: The Geometry of the Electrodes and Mesh Solution

Processes in Argon Plasma

Table 1 shows the chemical processes in argon plasma, which include elasticity, excitation and ionization processes with different cross-sectional energies. they are also known as volumetric reactions while table 2 shows the surface reactions of argon. The adhesion coefficient given in table 2 is the possibility of the atom returning to its original state when it hits the wall. Cross-section of gas reactions obtained from LXCAT [10].

Table 1: Argon Gas Reaction and Collisions [12]

Interactive formula		**type**	**(Δε (eV))**
1.	Ar +e ≥ e +Ar	Elastic	0
2.	Ar + e ≥ Ars + e	Excitation	11.5
3.	Ars + e ≥ Ar + e	Superelastic	-11.5
4.	Ar + e ≥ Ar^+ + 2e	Ionization	15.8
5.	Ars + e ≥ Ar^+ + 2e	Ionization	4.24
6.	Ars+ Ars≥ Ar^++Ar+e	Penning Ionization	-
7.	Ar + Ars ≥ Ar + Ar	Metastable quenching	-

Table 2: Argon Gas Reaction and Collisions [12]

Interactive formula		***Adhesion factor***
1	Ars ≥ Ar	1
2	Ar^+ ≥ Ar	1

The Results and Discussion

Using the Comsol Multiphysics program, a two-dimensional simulation of the DC glow-discharge plasma was carried out. The cathode must be grounded, and a positive voltage is supplied to the anode through an external circuit having resistance R and capacitor C connected in series with the discharge. The following results were obtained.

Electron Density

Electron density is what characterizes the properties and parameters of the resulting plasma. it was calculated in this model by solving a pair of electron density and average drift and scattering equations. Figure 2 shows the distribution of the electron density in the center of the discharge system, where it was found that when the voltage applied to the discharge system increased, it was found that most electrons rush towards the anode region, where they are accelerated due to the strong electric field, which leads to an increase in the electron density and reaches its peak in the region between the cathode glow and the positive column for further clarification was taken in the drawing in one dimension and along the line connecting the two electrods as in figure 3. These results were consistent with experimental studies, including the study conducted by the researcherand others, where this fact was proven [11].

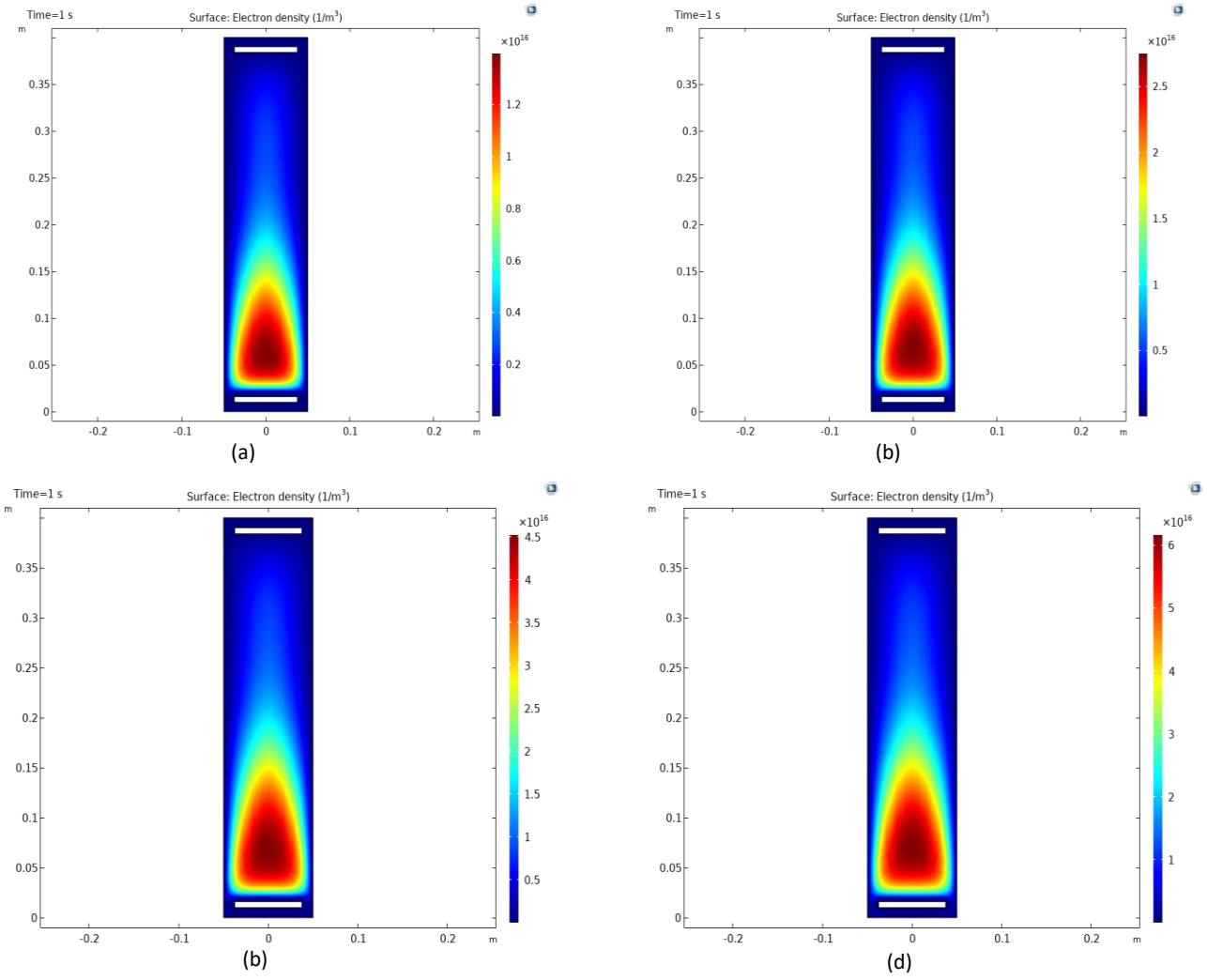


Figure 2: Distribution of Electrons Density in Relation to Axial Length at the Tube's Core at Various Voltages: (a) 125, (b) 145, (c) 165, (d) 185

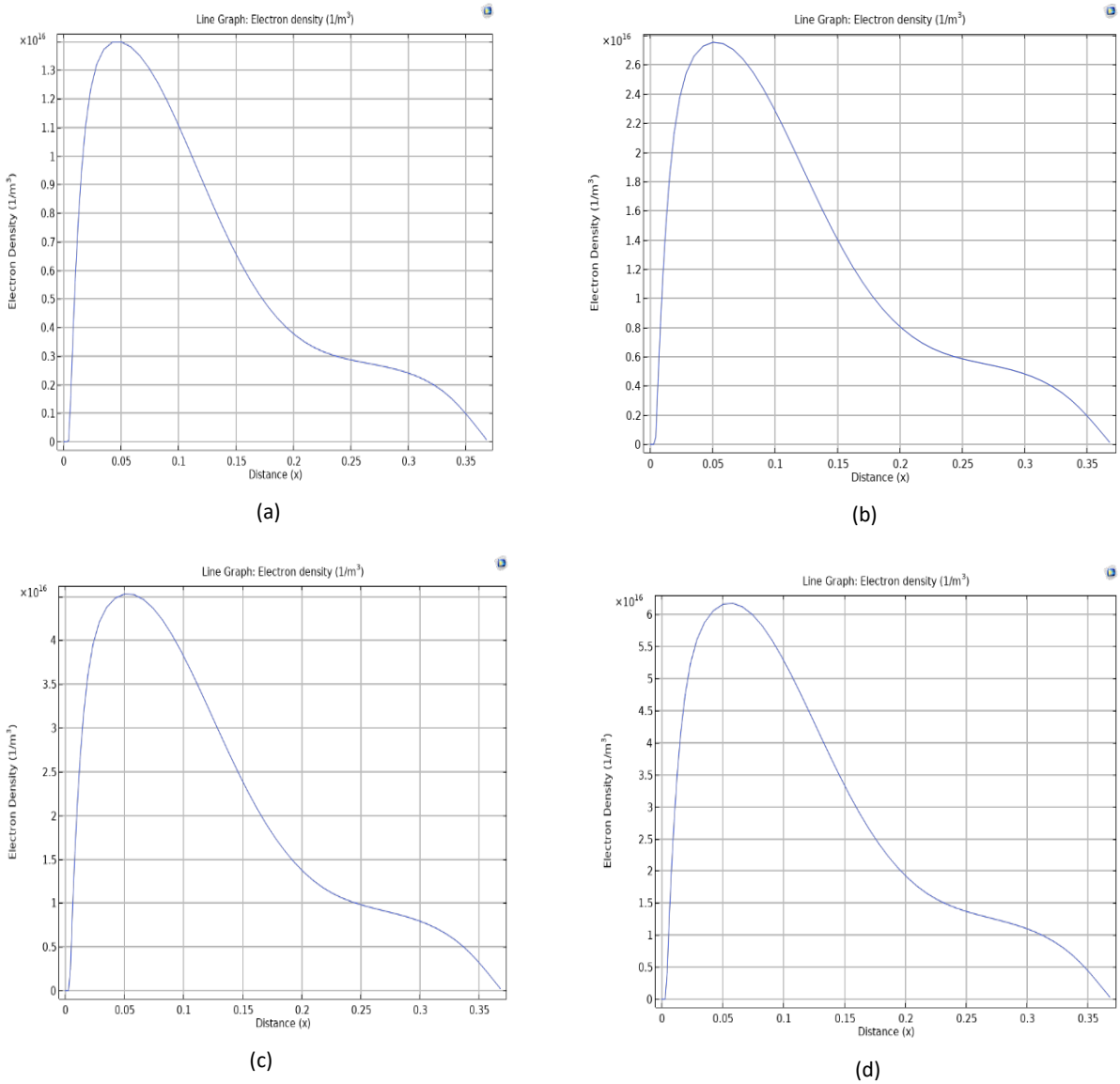


Figure 3: The Spatial Profile of Electron Density at Various Voltages. a) 125 V, b) 145 V, c) 165V, d) 185V torr

Electron Temperature

The temperature of the electrons is a key factor in determining the properties of the resulting plasma and determining its parameters. The electron temperature of the argon gas plasma was measured under the influence of pressure of 0.5 torr and voltage values 125, 145, 165 and 185 V. figure 4 shows that the temperature of the electron increases with increasing voltage, as observed that it is scattered radially in the cathode glow region. For more clarification, the drawing was taken along the line between the negative electrode and the positive electrode figure 5, when it was found that a strong electric field in the cathode region can cause high-energy ions to attack the cathode, which will then heat the cathode and cause it to emit thermal electrons as more electrons are emitted from its surface. The cathode has a high drift velocity along the dark space region column of the cathode, where secondary electrons with high kinetic energy are released after ions bombard the cathode, resulting in a peak electron temperature. These results were consistent with experimental studies, including the study conducted by the researcherand others, where this fact was proven [11].

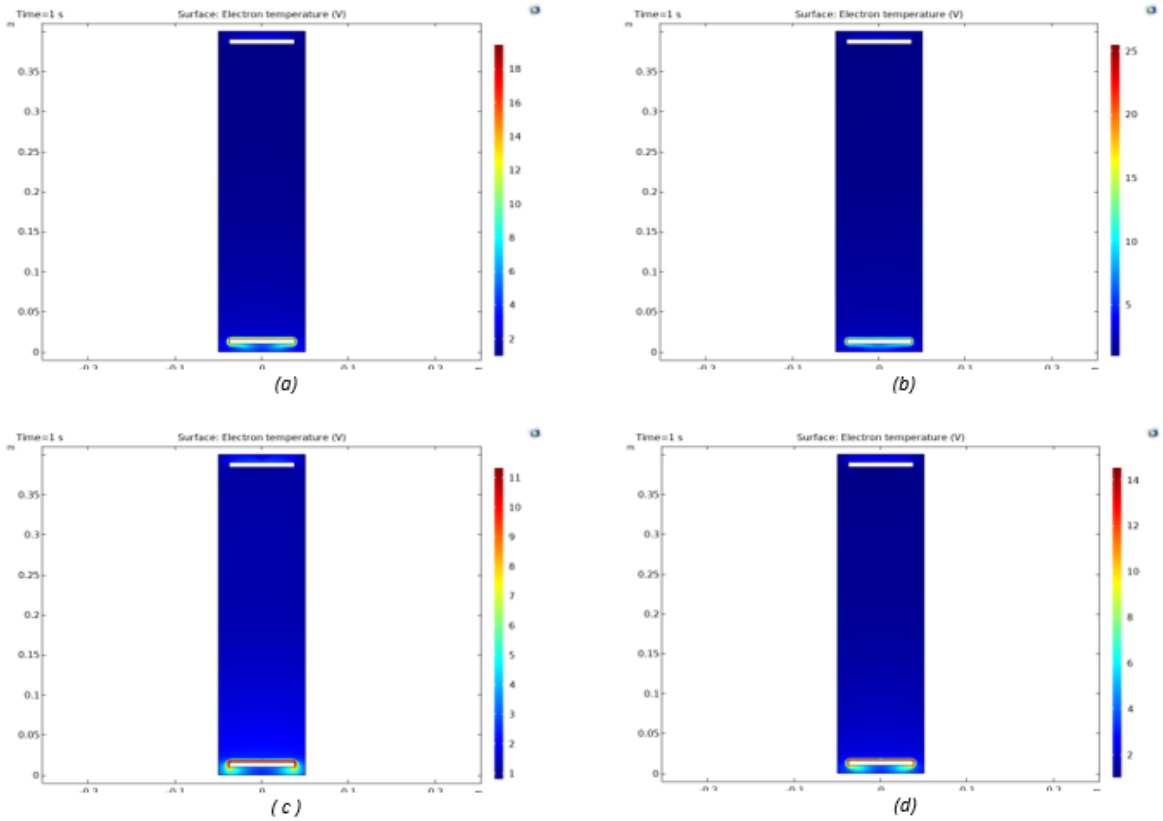


Figure 4: Distribution of Electron Temperature in Relation to Axial Length at the Tube's Core at Various Voltages: (a) 125, (b) 145, (c) 165, (d) 185

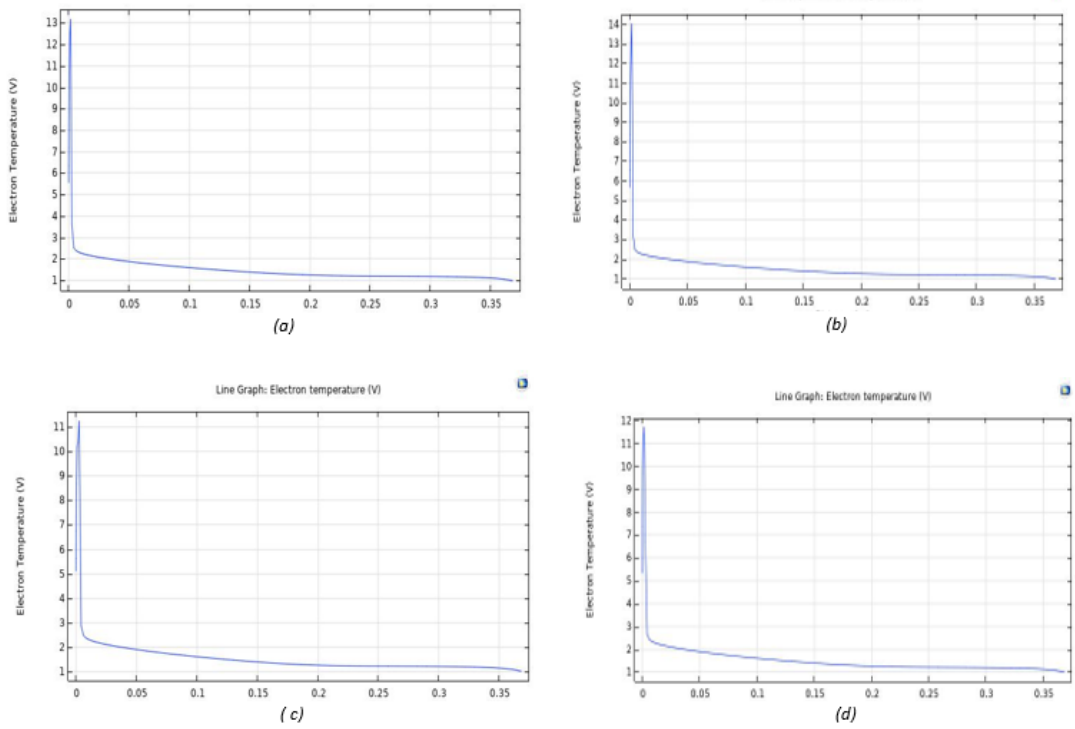


Figure 5: The Spatial Profile of Electron Temperature at Various Voltages (a) 125, (b) 145, (c) 165, (d) 185

Electric Potential

In figure 6, the external argon voltage distribution was measured against the length of the axis under the influence of pressure 0.5 torr and voltage values of 125, 145, 165 and 185 V. It has been observed that the electric potential increases with the increase in voltage. The figure shows the strong electric field in the cathode fall zone, where the concentration of ions is much higher than the concentration of electrons, and where the peak voltage demonstrates the accumulation of charged particles, primarily ions, is the primary reason why the electric potential decreases in this region. These results were consistent with experimental studies, including the study conducted by the researcherand others, where this fact was proven [11].

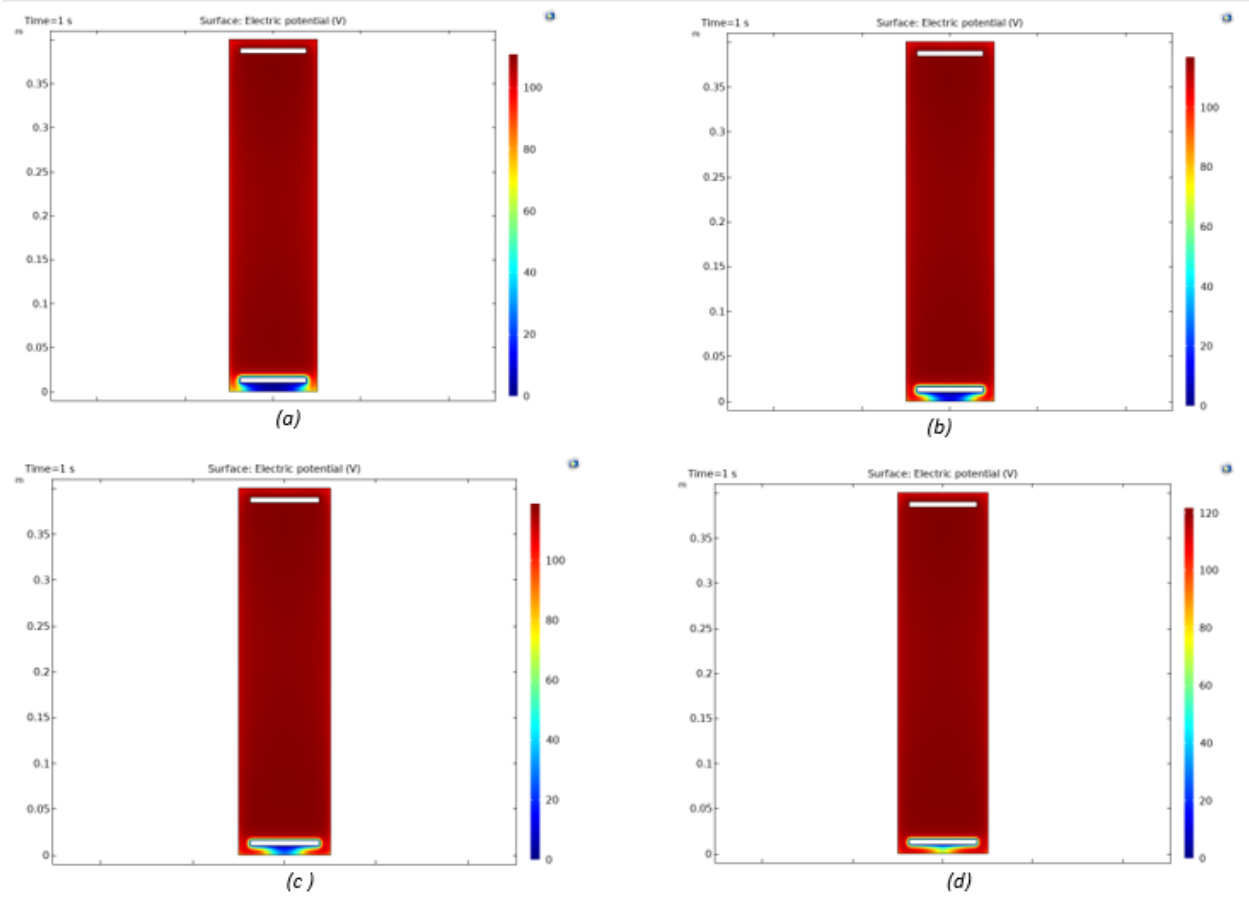
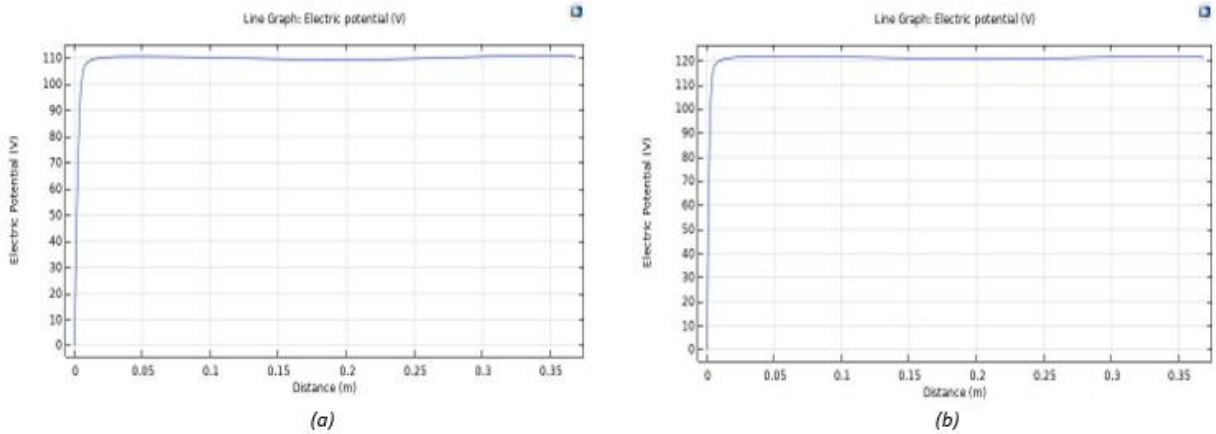


Figure 6: Distribution of Electric Potential in Relation to Axial Length at the Tube's Core, at Various Voltages: (a) 125, (b) 145, (c) 165, (d) 185



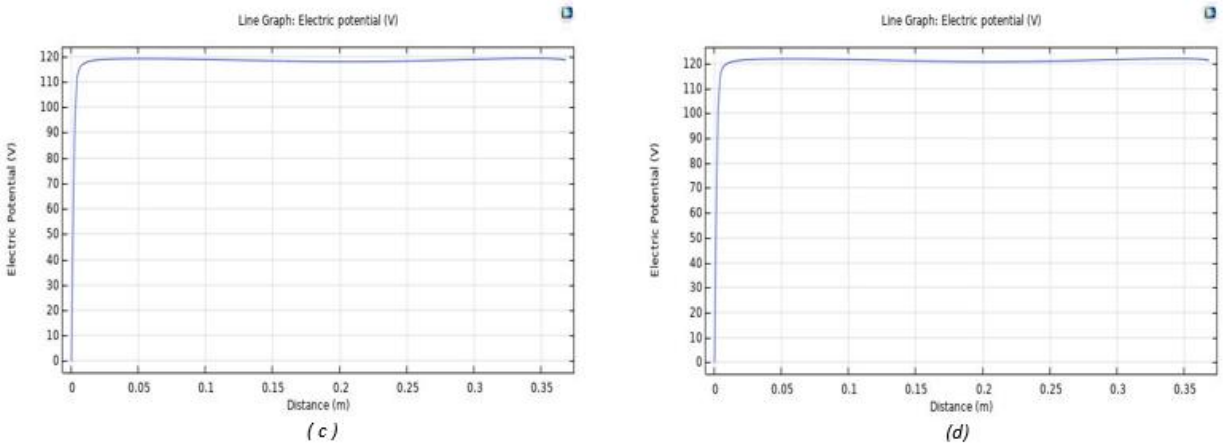


Figure 7: The Spatial Profile of Electric Potential at Various Voltages (a) 125, (b) 145, (c) 165, (d) 185

Ion Number Density

Figure 8 illustrates that when the voltage increases, the reaction area in the electrostatic discharge plasma increases along with an increase in the number of collisions, which leads to a clear increase in the density of ions because of the acceleration of the electrons emitted from the negative electrode towards the anode region as a result of the voltage increase. The ion density of argon gas was measured under the influence of pressure of 0.5 torr and voltage values 125, 145, 165, and 185V. It was found that the ion density peaks in the region between the positive column glow and the negative glow area. These results were consistent with experimental studies, including the study conducted by the researcherand others, where this fact was proven [11].

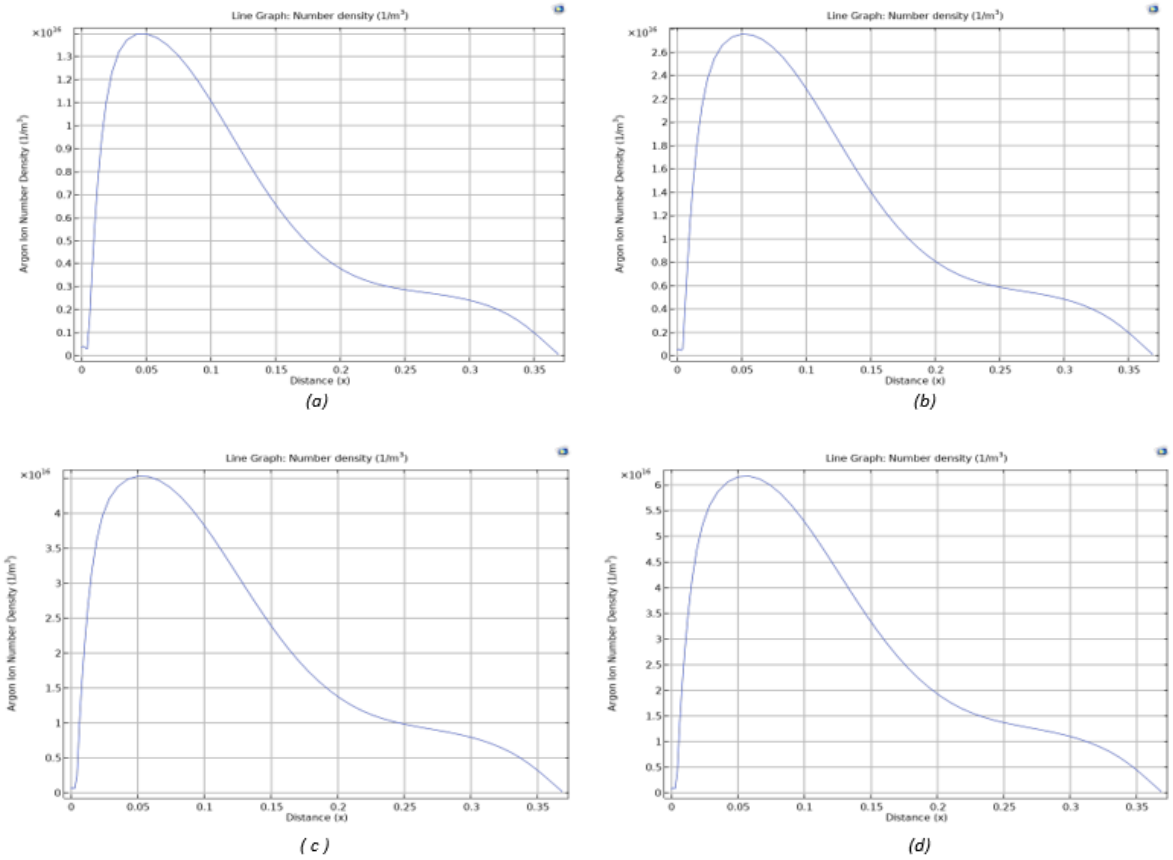


Figure 8: The Spatial Profile of Ion Number at Various Voltages (a) 125, (b) 145, (c) 165, (d) 185

Conclusions

To consider the effect of the applied voltage on the argon gas on the basis of the DC glow discharge problem, numerical simulation using the Comsol program was used, where a pair of electron density and electron energy were solved. The simulation was in two dimensions at pressure equal to 0.5 torr and different voltage values 125, 145, 165 and 185 V, and the electrode material used was aluminum with a work function of 4.08. The results showed that there is a clear effect of voltage on the parameters of the resulting plasma. It was found that the density of electrons, the temperature of the electrons, the electric potential and the density of ions will increase with the increasing of the voltage.

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