Design of a Plasma Jet System and Determination of Its Electronic Parameters for Use in the Treatment of Cancer Cells

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Abstract:The characteristics of atmospheric pressure plasma jets (APPJs) are of significant importance when used in various applications such as medicine, industry, and agriculture. In this work, a plasma tube was fabricated using poly-methyl methacrylate (PMMA) with specific geometrical dimensions to generate argon plasma jets. The generated plasma temperature was measured, and its relationship with the applied voltage was studied. Additionally, the effect of plasma with varying gas flow rates was investigated. The variation in plasma temperature over time was also analyzed, along with the relationship between the plasma column length and the gas flow rate. The intensity of the reactive species generated by the plasma was also measured using a spectrometer. Additionally, the electron temperature and electron density were calculated at different applied voltages. The results showed that the generated plasma temperature ranged between (27.2°C and 28.9°C). It was also observed that the plasma temperature increased with the increase in applied voltage within a specific range before stabilizing. Similarly, it was found that the plasma temperature increased with the gas flow rate and then stabilized. Additionally, it was noted that the plasma temperature changed over time within a certain range before reaching stability. Furthermore, the length of the plasma column increased with the gas flow rate. The measurements of electron temperature at different voltages indicated that the electron temperature increased with higher applied voltages. The results also showed that the electron density increased with the increase in applied voltage.
Key wards: *plasma jets, flow rate, electron temperature, poly-methyl methacrylate, Spectrometer*

1. Introduction

Over the past few years, the cold atmospheric pressure plasma (CAP) has emerged as a novel promising tool in medicine. As compared to the effects of the more conventional thermal plasma, cold plasma is selective in its treatment since it does not burn tissue [1]. Cold atmospheric pressure plasma (CAP) as a kind of non-equilibrium plasma can be produced in different configurations employed for the particular application [2]. In this research, the cold atmospheric pressure plasma jet has been used. This kind of plasma has been used in many fields, especially in biomedical applications [3]. Because of producing reactive oxygen and nitrogen species, especially atomic oxygen, hydroxyl radicals, and nitrogen oxides, these systems can affect live cells and organisms, microbes, etc. However, it should be mentioned that some applications of plasma in medicine relied mainly on its thermal effect [4]. It was suggested that some species have killing or healing effects [5]. One can use desirable configurations for different purposes, e.g., wound healing [6], decontamination of bacteria [7], cancer treatment [8], allergen inactivation [9], root canal disinfection [10], and vegetable treatment [11].

2. Devices and Methodology

Figure (1) presents a schematic diagram of the cold plasma system under atmospheric pressure, where an AC power supply (locally manufactured) with a frequency of 80 kHz and a voltage range of 2-5 kV was used to generate argon plasma. A plasma tube made from poly-methyl methacrylate (PMMA) with specific geometric dimensions was used, as shown in Figure (2). A copper electrode with a diameter of 1 mm was used, inserted into the inner cavity of the plasma tube through the top opening. Argon gas (Ar) with a purity of 99.99% was utilized for the electrical discharge. A gas flow meter of type RS 485 Modbus Digital (AMS206) was used to control the gas flow rate, which plays a significant role in determining the plasma jet column length as well as its effect on plasma temperature [12, 13].

A temperature measurement device of type MT-4606-C Infrared Digital Thermometer was used to measure plasma temperature accurately and to study the method of plasma temperature variation under different conditions, including (applied voltage, operating time, and gas flow rate). Given the significant importance of reactive species produced by cold plasma in medical applications, a spectrometer of type S3000-VIS Spectrometer (Figure 3) was used to measure the intensity of the reactive species produced at different voltages ranging between 2-5 kV.
Through the spectrum obtained, the electron temperature and electron density were calculated, along with their relationships with the applied voltage.

The Boltzmann method was employed to analyze the emitted spectra of plasma to calculate the electron temperature (Te) and electron density (ne). This method relies on comparing the intensities of spectral lines and their distribution, which follows the Boltzmann relation describing the energy distribution of electrons in the plasma. The electron temperature was calculated using the Boltzmann equation:

$$\ln\left(\frac{I_{ul}\cdot\lambda}{g_u\cdot A_{ul}}\right) = -\frac{E_u}{k_B\cdot T_e} + \ln\left(\frac{hc}{Z(T)}\right)$$

By plotting the logarithmic relation between the spectral line intensity and the upper energy level (E_u), the slope of the line is inversely proportional to the electron temperature (T_e).
The electron density (ne)was calculated using the Full Width at Half Maximum (FWHM) of the spectral lines due to the Stark broadening effect:

$$n_e = \frac{FWHM \cdot C}{\sqrt{T_e}}$$

C: Stark broadening coefficient for the corresponding spectral line.

Table 1. : Electron temperature (Te) and electron density (ne) at different voltage

Voltage (V)	T_e(eV)	ne $\times 10^{15}$ (cm^{-3})
2000	4.02	5.9
2500	4.04	6.91
3000	4.08	7.3
3500	4.14	7.42
4000	4.24	7.83

The following measurements and calculations were conducted:

3. **Measuring Plasma Temperature:**

- The relationship between the plasma operating time and the plasma temperature at different voltages (2 kV, 3 kV, 4 kV). Fig. (4)
- The relationship between the gas flow rate and the plasma temperature.Fig. (5)
- The relationship between the applied voltage and the plasma temperature. Fig. (6)
- The relationship between the plasma operating time and the plasma temperature at different distances from the nozzle opening (0 cm, 1 cm, 1.5 cm). Fig. (7)

4. **Measuring Plasma jet Length:**

- The effect of gas flow rate variations on the length of the plasma column was studied under a constant applied voltage of 3 kV. Fig. (8)

5. **Diagnosing Reactive Species (Reactive Species Analysis):**

- Instrument Used: The S3000-VIS Spectrometer was employed to diagnose the reactive species produced by the cold plasma system.
- Experimental Procedure:
    - ➢ The reactive spectrum was analyzed to identify and measure the intensity of the reactive species generated by the plasma.
    - ➢ Measurements were conducted at different voltages (2 kV, 3 kV, 4 kV, and 5 kV) to assess the impact of voltage on reactive species formation. Fig. (9)
    - ➢ Additionally, the following parameters were calculated:

- Electron Temperature & Electron Density: Derived from spectral analysis using the Boltzmann Method.
- Study the effect of applied voltage on both Electrons temperature and electron density. Fig. (10)

6. Results and Discussion

The study demonstrated the influence of several factors (voltage, time, gas flow rate, and distance) on the properties of argon plasma, analyzing its temperature and plume length based on these variables. The first graph, which illustrates the relationship between time and temperature at different voltage levels (2 kV, 3 kV, and 4 kV), showed that the temperature increases over time for all voltage values. The highest temperatures were observed at the highest voltage (4 kV). This result confirms that increasing the voltage leads to a higher kinetic energy of electrons within the plasma, thereby increasing the temperature due to enhanced plasma activity. Regarding the relationship between voltage and temperature at a fixed time (1 minute), the graph revealed a nearly linear relationship where the temperature increased significantly with higher voltage. This reflects the direct impact of the applied voltage on the internal energy of the plasma, making it possible to regulate the plasma temperature by controlling the voltage to meet specific application requirements.

The effect of the distance between the plasma and the measured point was also examined. The graph indicated that the temperature was highest at the closest distance (0.5 cm) and gradually decreased as the distance increased. This can be attributed to the fact that proximity to the plasma source allows for a more accurate measurement of thermal energy, while increasing the distance results in heat dissipation.

Regarding the influence of gas flow rate on temperature, the results showed that the temperature increased with higher flow rates, peaking at the highest flow rates (15-16 L/min). This can be explained by the improved stability of the plasma at higher flow rates due to the increased supply of electrons and energy, which helps maintain plasma activity.

Finally, the relationship between gas flow rate and plasma plume length showed that the plume length decreased with increasing flow rates. The longest plume length was observed at lower flow rates (7 L/min), while it shortened to smaller values at higher flow rates. This behavior might be attributed to plasma dispersion at higher flow rates, which reduces its concentration and, consequently, its plume length. Overall, these results confirm that controlling the studied parameters can help regulate plasma properties to meet the requirements of specific applications, such as medical or industrial uses. Further experiments are recommended to determine the optimal conditions and ensure system stability under various operating scenarios.

The spectral analysis of the argon plasma at varying applied voltages (2 kV to 4 kV) and a fixed gas flow rate of 10 L/min provided valuable insights into the behavior of the plasma and its interaction with the surrounding environment and system materials. The results demonstrated distinct emission peaks corresponding to key elements involved in the plasma dynamics, including argon, oxygen, and silicon.

The emission spectrum revealed notable peaks at specific wavelengths, with the most prominent peaks belonging to neutral and ionized argon. Peaks in the range of 285 nm to 400 nm represented high-energy transitions of neutral argon atoms, while those in the range of 700 nm to 800 nm were attributed to ionized argon, becoming particularly prominent at higher voltages (4 kV). The increased intensity of these peaks with higher voltages indicates that the electron kinetic energy within the plasma was enhanced, leading to more frequent collisions and greater ionization.

Interestingly, two significant peaks were identified as belonging to oxygen at 297 nm and 320 nm. These peaks suggest the presence of ionized oxygen within the plasma, likely originating from residual gases in the system or the surrounding environment. The intensity of these peaks increased with voltage, indicating that higher energy inputs promote more efficient oxygen ionization. Additionally, the presence of oxygen emissions provides evidence of interactions between the plasma and its immediate surroundings. Another noteworthy feature was the peak at 780 nm, which corresponded to silicon. This emission likely resulted from interactions between the plasma and the materials within the system, such as electrodes or surface contaminants. The silicon peak highlights the impact of plasma-surface interactions and suggests potential sputtering or material release from system components under the influence of high-energy plasma.

In parallel, the relationship between applied voltage, electron temperature (Te), and electron density (n_e) was examined. It was observed that electron temperature increased slightly with increasing voltage, reaching approximately 4.2 eV at 5000 V. This reflects an enhancement in the internal energy of the system, enabling more energetic reactions within the plasma. Simultaneously, electron density exhibited a significant rise, increasing from approximately 14,000 electrons/cm^3 at 1000 V to 22,000 electrons/cm^3 at 5000 V. The increase in electron density signifies a higher concentration of active particles, resulting in a denser and more stable plasma.

These findings suggest that higher voltages enhance the energy and density of electrons, thereby improving the overall activity and stability of the plasma. This is further supported by the increased intensity of spectral emissions at higher voltages, which indicates more pronounced ionization and greater plasma reactivity. The presence of oxygen and silicon peaks also highlights the importance of understanding plasma interactions with surrounding gases and system materials, as these interactions can influence both the plasma properties and system performance.

In summary, the results demonstrate that applied voltage is a critical parameter in controlling the characteristics of argon plasma. By optimizing voltage, it is possible to enhance plasma density, electron temperature, and ionization efficiency, making the system suitable for various applications such as surface modification, material processing, and medical treatments. Future studies could focus on investigating the role of other system parameters, such as gas composition and pressure, to further refine plasma properties and expand its potential applications.

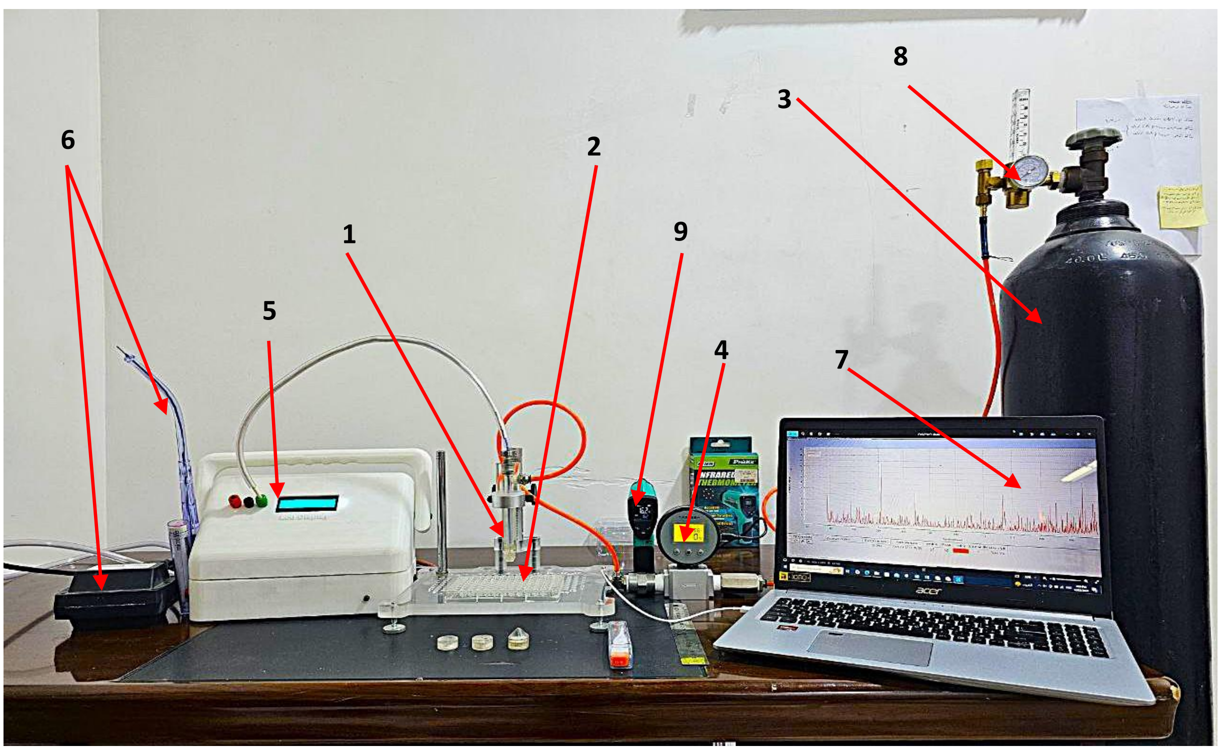
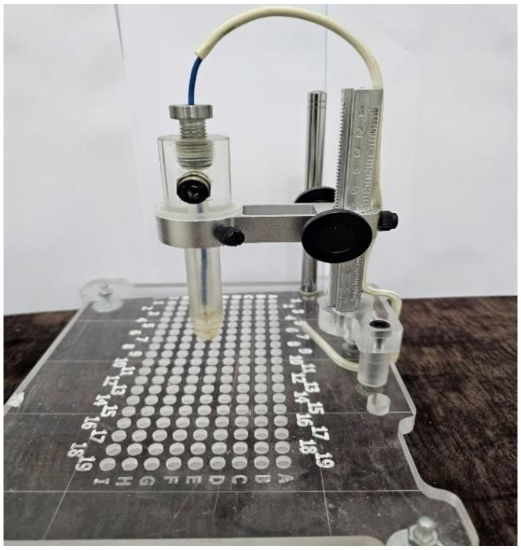


Figure (1) schematic diagram of the cold plasma system under atmospheric pressure 1. plasma tube, 2. plate-96, 3. argon gas, 4. digital flowmeter, 5. power supply ,6. spectrometer (s3000-VIS), 7. laptop, 8. gas manometer, 9. IR Digital thermometer



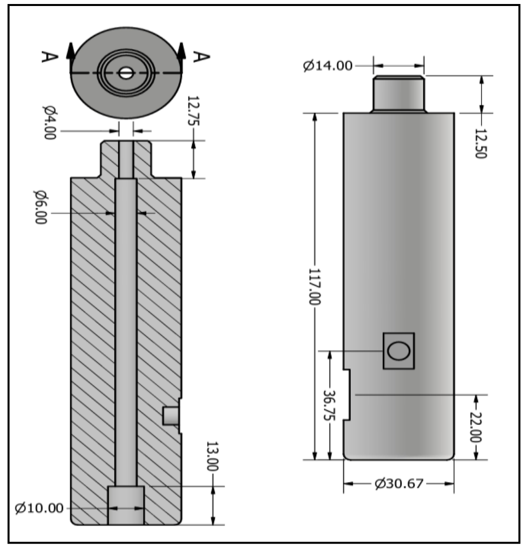


Figure 2: Schematic of the cold plasma tube, b. Manufactured cold plasma system

Figure 3: S3000-VIS spectrometer

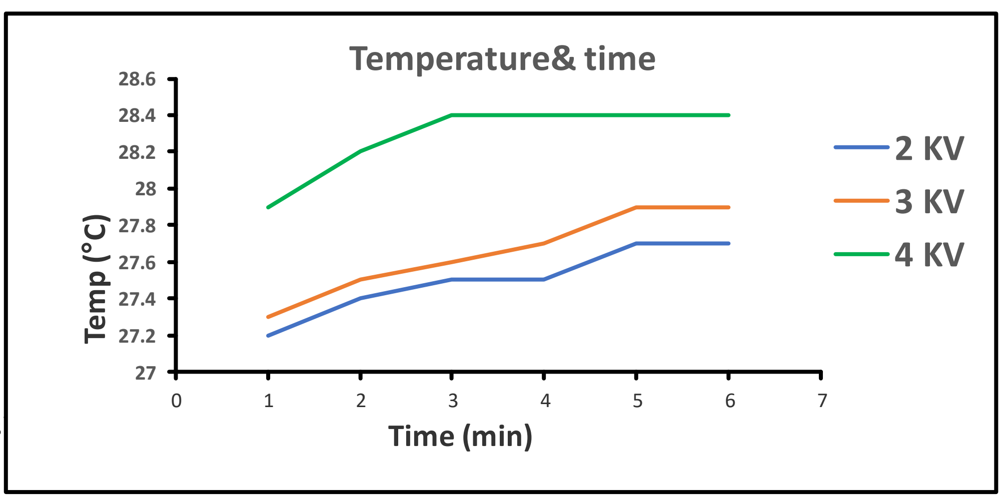


Figure 4: Relationship between operating time and plasma temperature at different voltages

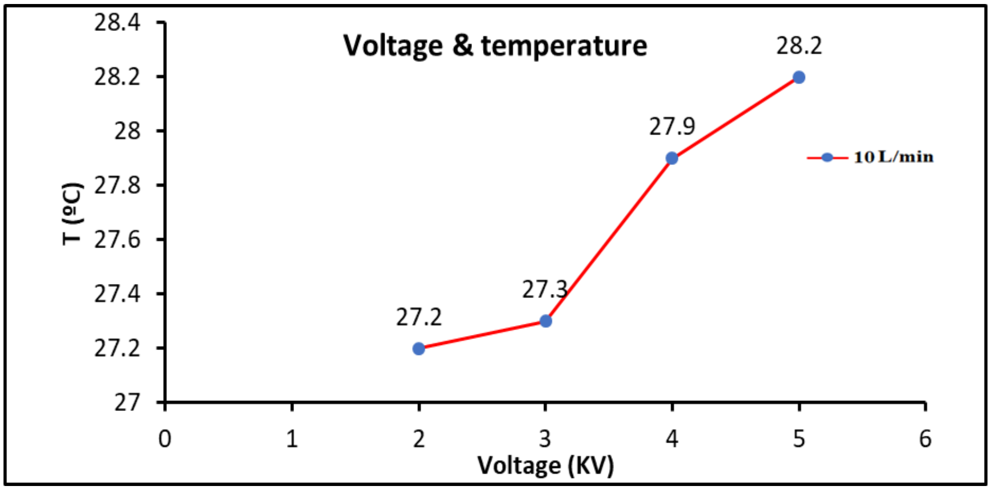
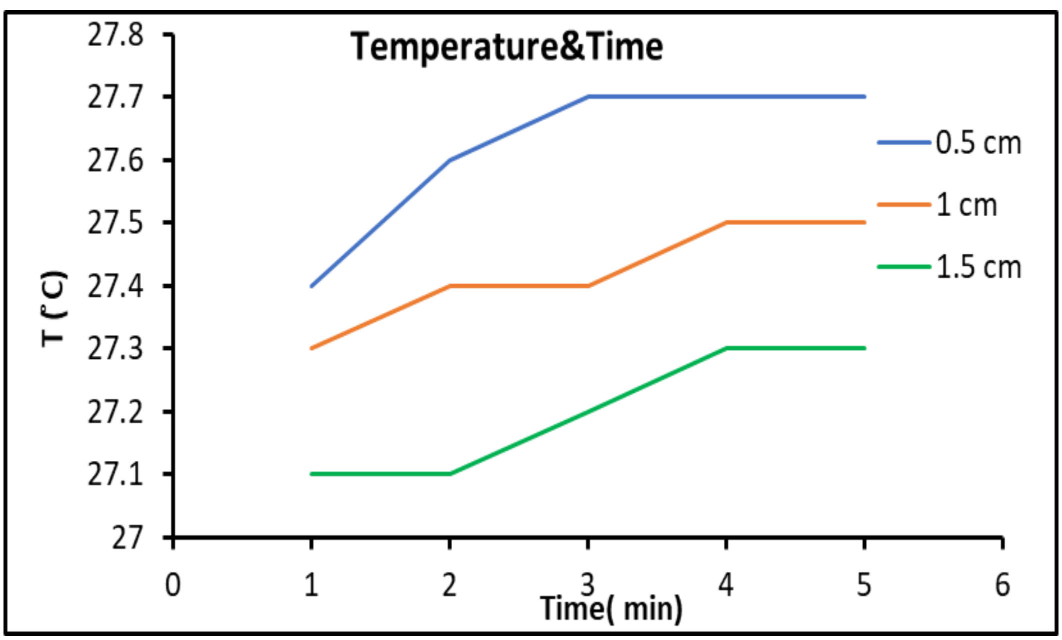


Figure 5: Relationship between applied voltage and plasma temperature at a flow rate of 10 l/min.



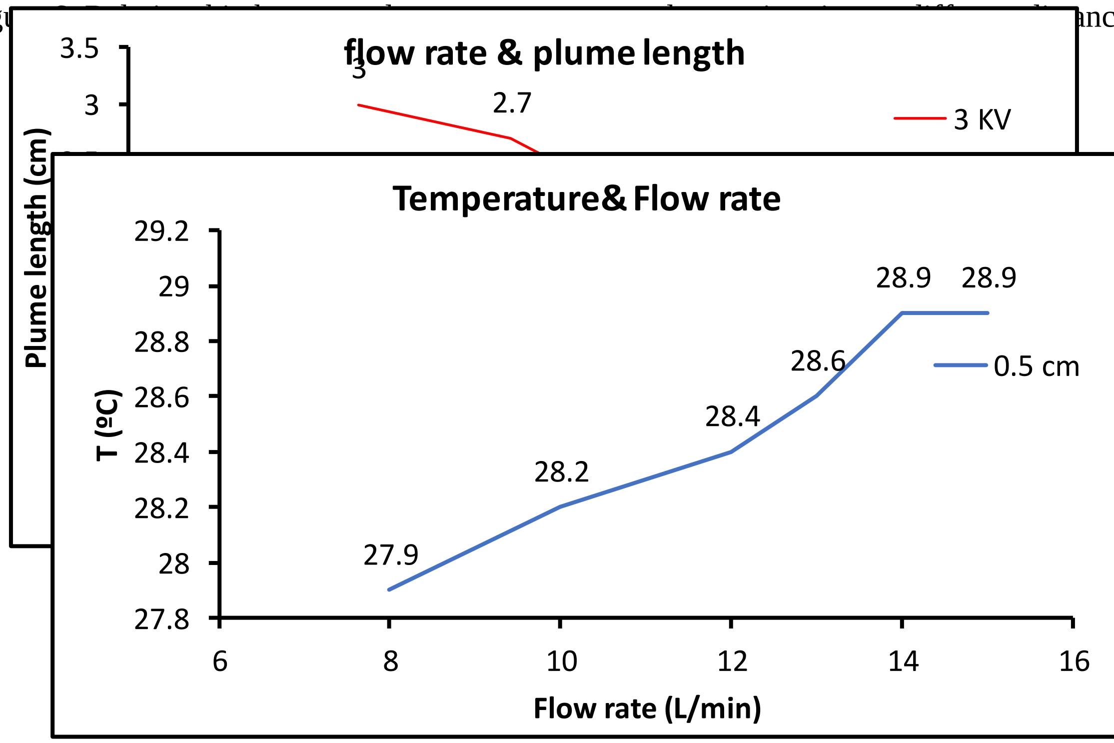


Figure 7: Relationship between plasma temperature and gas flow rate

Figure 8: Relationship between plasma column length and gas flow rate at 3 kV voltage.

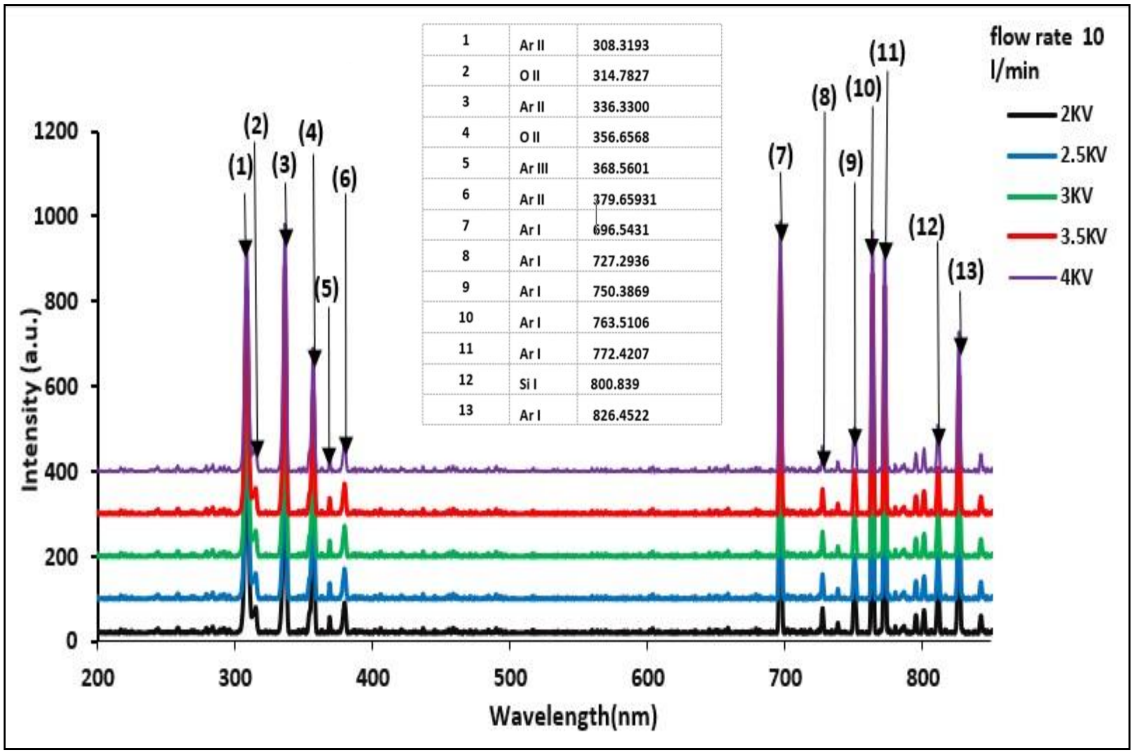


Figure 9: Diagnostics of optical emission of single electrode plasma jet AC system at (2-4 KV)

Cues

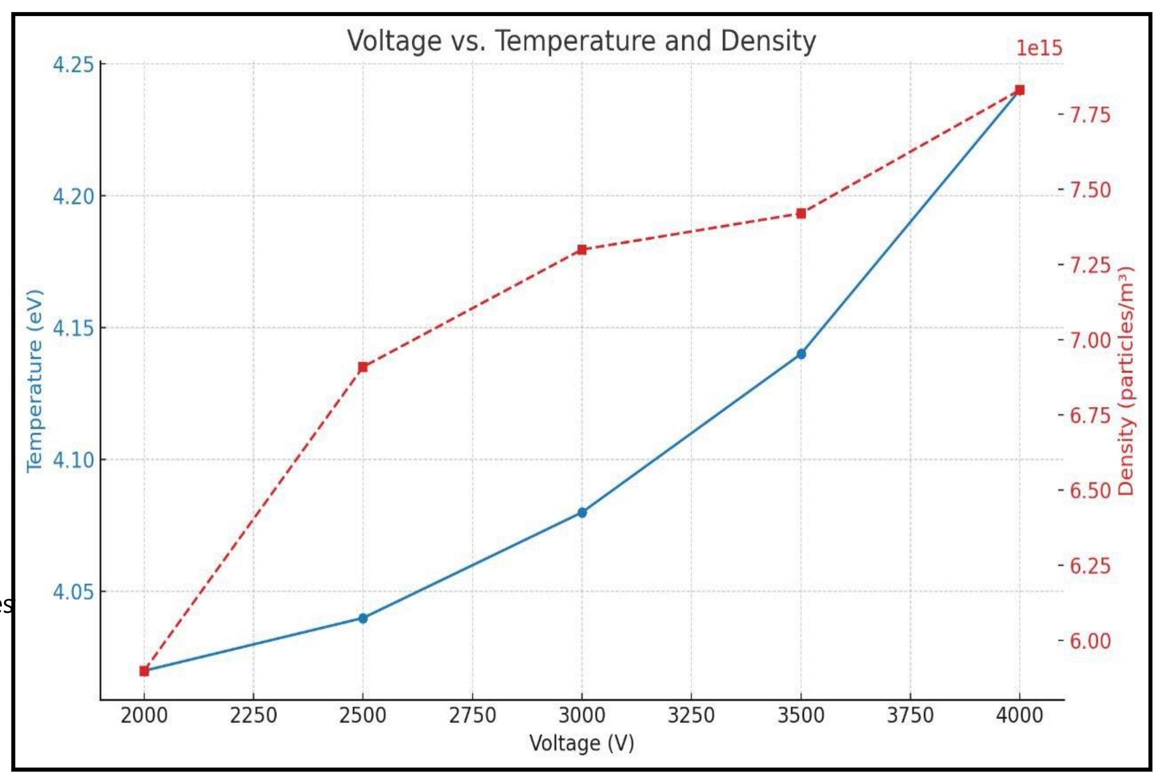


Figure 10: Relationship between the electron temperature, the electron density, and the applied voltage.

7. Conclusions

In this study, a cold plasma jet system was designed and assembled, this system thus offers significant potential for biological applications, particularly in medical fields such as cancer treatment and tissue sterilization, the system produces plasma temperatures between 27.2°C and 28.9°C, ensuring thermal safety without damaging living tissues. Its stability over time and under varying conditions is crucial for reliability. The plasma's electronic properties show increased electron temperature and density with higher applied voltages, leading to greater production of reactive chemical species. Spectral diagnostics reveal peaks for elements like argon, oxygen, and silicon. The optimal operating conditions include a voltage range of 3-4 kV, a gas flow rate of 10-12 L/min, a distance between the nozzle, and target between 0.5, and 1 cm, and an operational duration of one to three minutes.

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