Development of Low-Temperature Atmospheric Plasma Jet Sources for Biological Applications

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Abstract

   The research aims to develop and build a plasma jet system operating under atmospheric pressure.for biological purposes. The advanced plasma system consists of a power supply and a plasma torch. The source of the development of the system is a previous laboratory system that was developed by changing the voltage and frequency of the power supply, as the power provider equips the system with a voltage in the form of a sine wave whose value is fixed at about (7.5kV) peak to peak and its frequency is about (28 kHz). The plasma torch consists of a teflon tube with of width of (10 m) located at (10mm) from the end of the tube. The current waveform and voltage wave were measured using a current and voltage sensor and an oscilloscope. The plasma jet was characterized. Electron temperature and electron density vary with the gas flow rate; the length of the plasma jet depends on the flow rate of argon gas, and the best length of jetting plasma was (1.5 cm) at a flow rate of (2.5 l/min). The gas temperature was measured by an infrared thermometer at a constant flow rate of (2.5 l/min) which is (18°C) after 15 minutes of irradiation. From these results, it was concluded that the developed plasma is suitable for biological applications.

 Keywords: Plasma jet, Optical emission spectroscopy, Argon gas, Atmospheric pressure plasma .

تطوير مصادر بلازما النفث منخفضة الحرارة وعند الضغط الجوي للتطبيقات البيولوجية

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الخلاصة

    يهدف البحث إلى تطوير وبناء منظومة بلازما تعمل عند الضغط الجوي النفث للأغراض البيولوجية.تتكون منظومة البلازما المتطورة من مجهز قدره وشعلة بلازما. حيث ان مصدر تطوير المنظومة هو من خلال منظومه مختبرية سابقه تم تطويرها من خلال تغيير الفولتية والتردد لمجهز القدرة حيث ان مجهز القدرة يجهز المنظومة بفولتية على شكل موجة جيبية تكون قيمتها ثابتة وهي حوالي (7.5 كيلو فولت) من الذروة إلى الذروة ويبلغ تردده حوالي (28 كيلو هرتز). تتكون شعلة البلازما من أنبوب تفلون بقطر داخلي (5 مم) وقطب كهربائي رقيق من الألومنيوم يوضع على أنبوب تفلون بعرض (1مم) وعلى بعد (10 مم) من نهاية الأنبوب. تم قياس شكل موجة التيار وموجة الفولتية باستعمال مجس للتيار والفولتية وراسم الذبذبات يكون خازن نوعه (LINI−T) وقد تميزت بلازما النفث بإيجاد ان درجة حرارة الالكترون وكثافة الالكترون يتغيران مع معدل التدفق وطول نفائة

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البلازما ويعتمد على معدل تدفق غاز الاركون، وأفضل طول لبلازما النفث كان (1.5 سم) عند معدل تدفق
(2.5 لتر / دقيقة) . تم قياس الغاز بواسطة ميزان حرارة الأشعة تحت الحمراء مع تدفق ثابت قدره (2.5 لتر /
دقيقة) وهو (18سيليزية) بعد 15 دقيقة من التشعيع. من هذه النتائج نستنتج أن البلازما المطورة مناسبة للتطبيقات
البيولوجية.

Introduction

   Cold Air Pressure Plasma (CAPP) technology has attracted a lot of interest recently because of its appealing properties, such as operational simplicity, low operating costs, and environmental friendliness. Plasma at atmospheric pressure, low temperature, and CAPP is a strong instrument for killing bacteria, viruses, and fungi. Cold air pressure plasma technology is novel, powerful, and versatile, with a wide range of applications[1]. Because of its numerous uses in health care, medicine, environmental treatment, pollution control, materials processing, electrochemistry, nanotechnology, and other sectors, unbalanced atmospheric pressure plasma has recently been a hot research topic [2].

   Physical plasma, in general, is a partially ionized gas made up of neutral ions, electrons, atoms, and excited molecules that can generate UV radiation. Plasma treatment is widely chosen for sterilization, surface cleaning, and surface modification to alter physical and chemical properties, as well as to improve surface biocompatibility [3]. Plasma sources vary widely, making it impossible to summarize or even compare physical and biological data from different sources [4]. Atmospheric pressure plasma jets (APPJ) have a 50-year history, during which time their design and plasma generating mechanism have been refined and applied to a various uses [5]. The pressure of plasma in the atmosphere APPJ is a type of cold plasma discharge that produces a high-velocity stream of highly reactive chemical species with very little light emitted. The inner electrode of an APPJ is commonly coupled to a high-frequency RF or MW power source, generating ionization. The working gas is mostly a noble gas like helium or argon, and it comes out of a nozzle as a jet. Plasma pens, plasma torches, and plasma needles are all options [1].To comprehend the impact of various operations, it is vital to grasp the properties of plasma. Electrical samples and optical emission spectroscopy are among the diagnostics available. Only probes have traditionally been employed to assess electron streak and temperature. Plasma temperature is a crucial thermodynamic variable that determines and predicts various plasma properties [6]. Employing argon as a carrier gas allows the gas to remain at ambient temperature even after hours of operation .No irritation associated with plasma or argon gas. Optical emission spectroscopy was used to study a plasma jet, and it was determined that high-energy electrons, ionized atoms, molecules, and UV photons are the primary factors responsible for the effective reduction of microorganisms. [7]. Other than heat, several types of reactive oxygen and nitrogen were discovered to correspond to electrons, ultraviolet rays, ions, photons, and electric fields in atmospheric pressure plasma [8]. APPJs are becoming increasingly important for efficient production of reactive oxygen and nitrogen species (RONS) in fluids and aqueous media, such as biological fluids, due to their ability to transport RONS to treated tissues and organs and their significant impact on fluid dynamics [9].

   This study aims to develop APPJs to produce a reactive plasma that can be applied in biomedical applications including the inactivation of herpes viruses. The action of APPJs with argon gas had maximum emission intensity of reactive radicals and the best killing effect.

2-Experimental work
1-2-Plasma torch configuration:-

   The APPJs plasma torch is shown in Figure 1. The system that generates the plasma consists of a teflon tube surrounded by aluminum foil (10mm) wide and(10 mm) away from its end. The aluminum foil is connected to a the high-voltage power source that gives a sinusoidal waveform voltage of 28 kHz frequency and (7.5kV) peak to peak voltage.
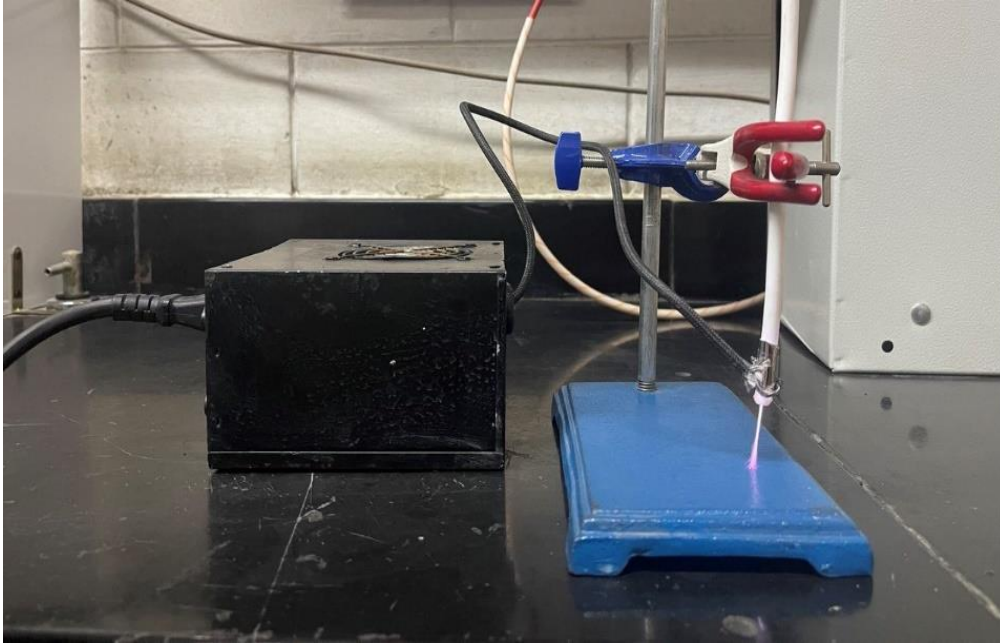

Figure 1: Dielectric barrier discharge (DBD**)** Non-thermal atmospheric pressure plasma torch

2-2-Electrical Diagnostic:-

   Waveforms of the current and voltage of the power supply were measured with a high voltage probe and current probe. Oscilloscopes type (LINI-T) was used to record the voltage and current.

3-2-Optical Emission Spectra (OES):-

The active species in the plasma jet were determined from the emission spectra recorded by a spectrophotometer in the range (of 300-1000) nm, as shown in Figure 2.
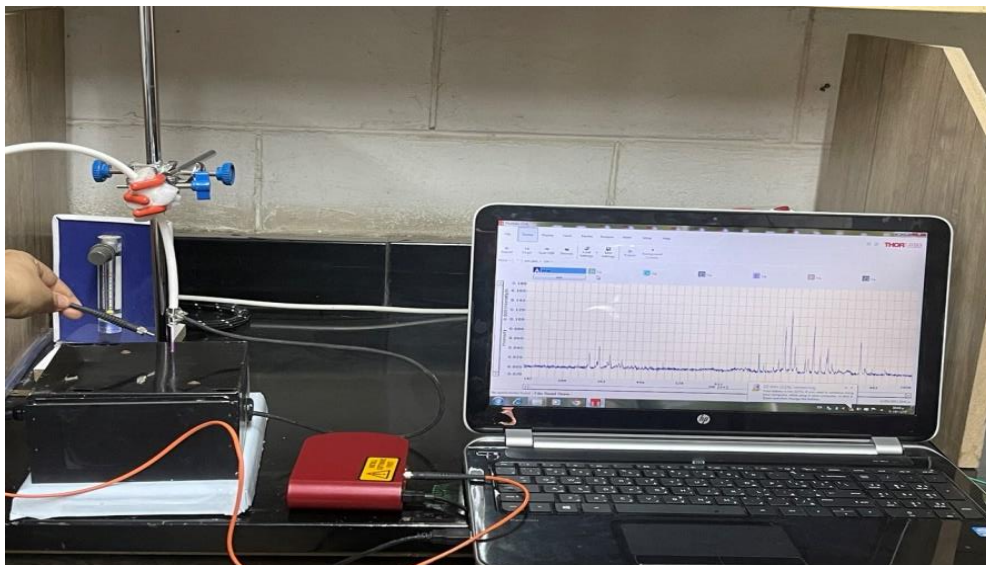
Figure 2: Plasma production system and the spectral analyzer

4-2-Working Gas Temperature Measurement:-

The working gas temperature was measured with an infrared thermometer where wafers were positioned at a specific location from the torch's end. The temperatures, at the specific location and at a constant Ar gas flow rate of (2.5l\m), were registered immediately as the plasma jet struck the wafer

5-2-Plasma Jet Length:-

The length of the plasma jet was measured using a mobile camera to image the jet at various working gas flow rates to be compared with previous work [10].

3- Results and Discussions
1-3-Electrical Diagnostic:-

Figure 3 shows the waveforms of current and voltage resulting from the electrical diagnosis. As seen, the resulting voltage is a smooth sinusoidal waveform without spike lines, as well as the corresponding peak-to-peak current, is sinusoidal with decay waveforms. The frequency of the power supply was around 28 kHz.
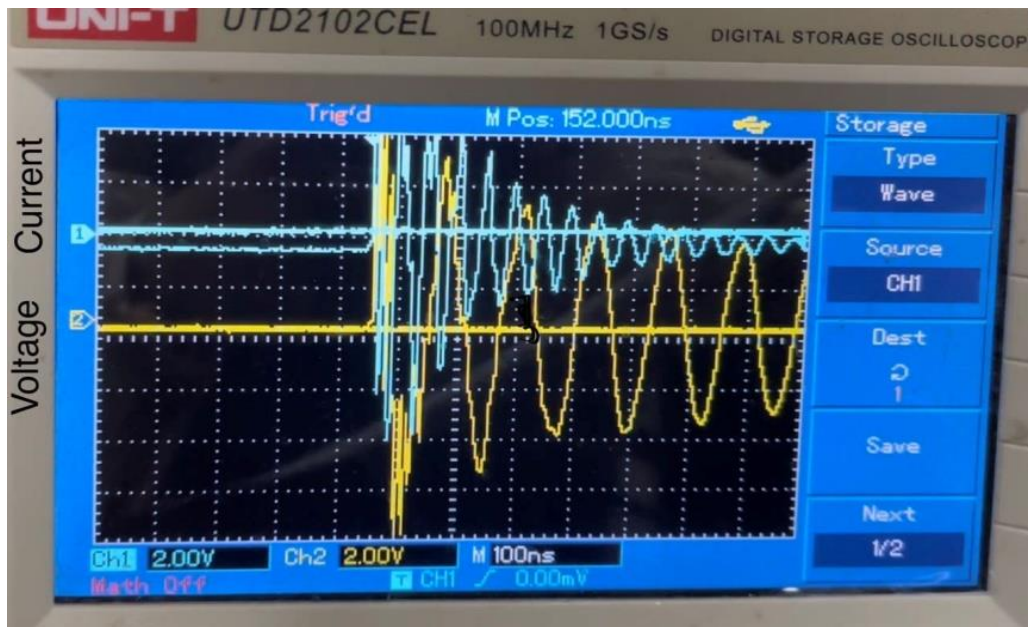

Figure 3: The waveform of the voltage and current pulse of the plasma jet.

2-3- Optical emission spectra :-

Figure 4 shows the plasma spectra recorded with a spectrophotometer to determine the electron temperature, electron density, and other plasma parameters. The flow rate of argon gas was changed from (0.5-4.5 l / min). The intensity of the spectra peaks increased with the increase of the gas flow rate to a certain extent and then began to decrease, meaning that there is an average limit to the gas flow rate for which the highest peak intensity appears.
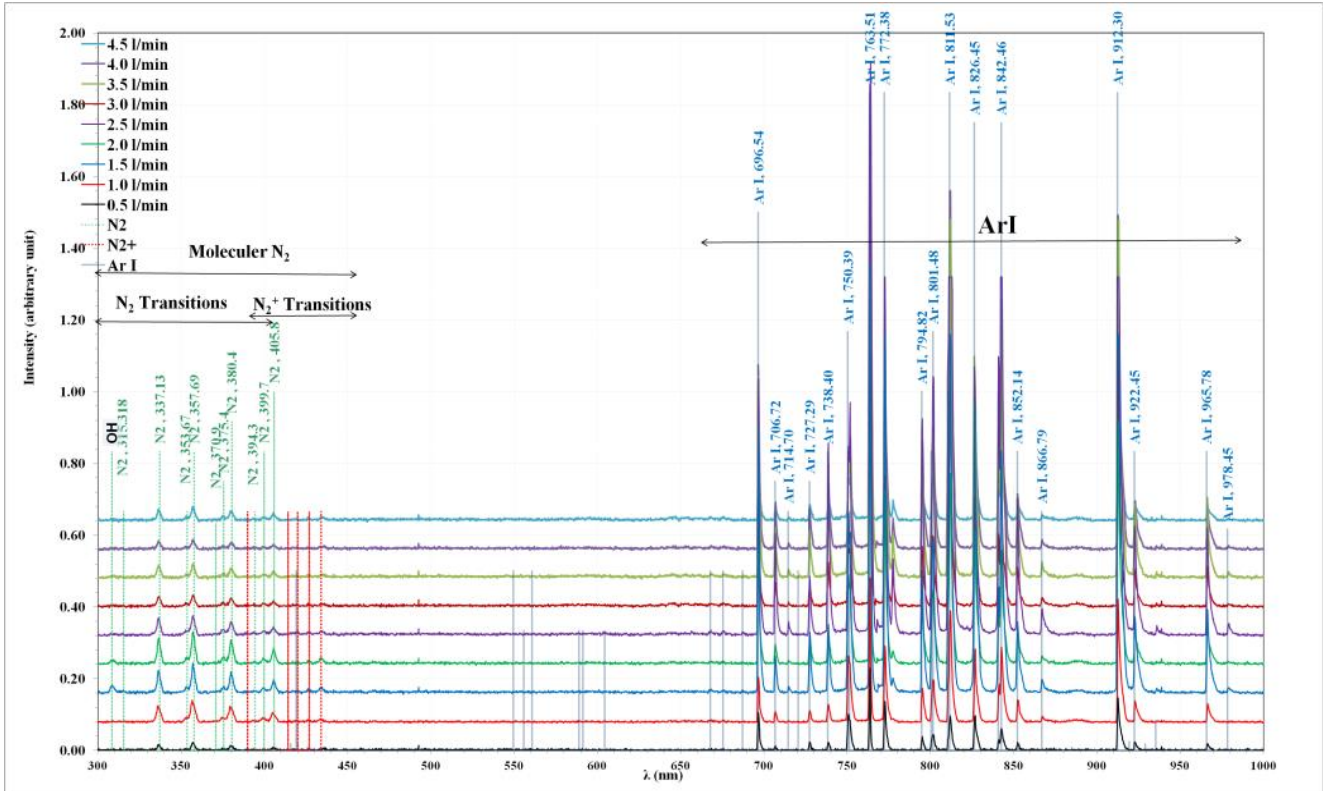
Figure 4: The APPJs spectra for different gas flow rates

It was observed that argon (Ar) and nitrogen(N_2) emission lines appeared. Ar emission lines were dominant as it is the working gas; while those for nitrogen were weak because the amount of N_2 is less and its source is atmospheric air. The peaks'location are identical to the standard peaks for the emission lines. The emission lines were ArI and N_2 lines, in addition to N_2, spectra of hydroxide (OH) were also observed, The peaks at 315, 353, 370, 375, and 380nm, correspond to a group of N_2 emissions in the form of a second positive system (SPS). The peaks at 414, 420,426, and 436 nm are the first negative system (FNS) for N_2.

3-3- Electron temperature(Te) and the electron density(n_e) :-
Depending on Equation 1, Boltzmann curves were drawn to find the electron temperature (T_e).

$$\mathrm{Ln}\left[\frac{\lambda_\mu I_\mu}{hc\ A_{ji}g_j}\right] \ = \ -\frac{1}{KT}\ (E_j) + \mathrm{Ln}\left[\frac{N}{U(T)}\right] \tag{1}$$

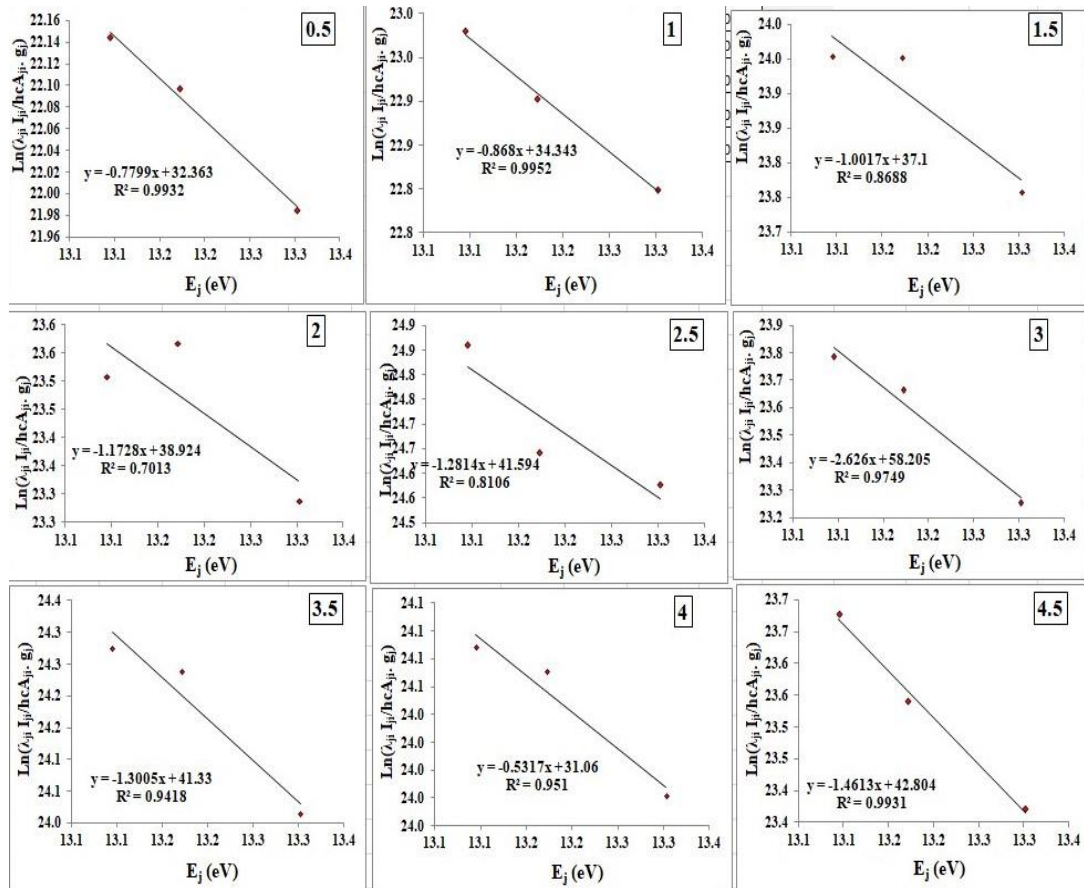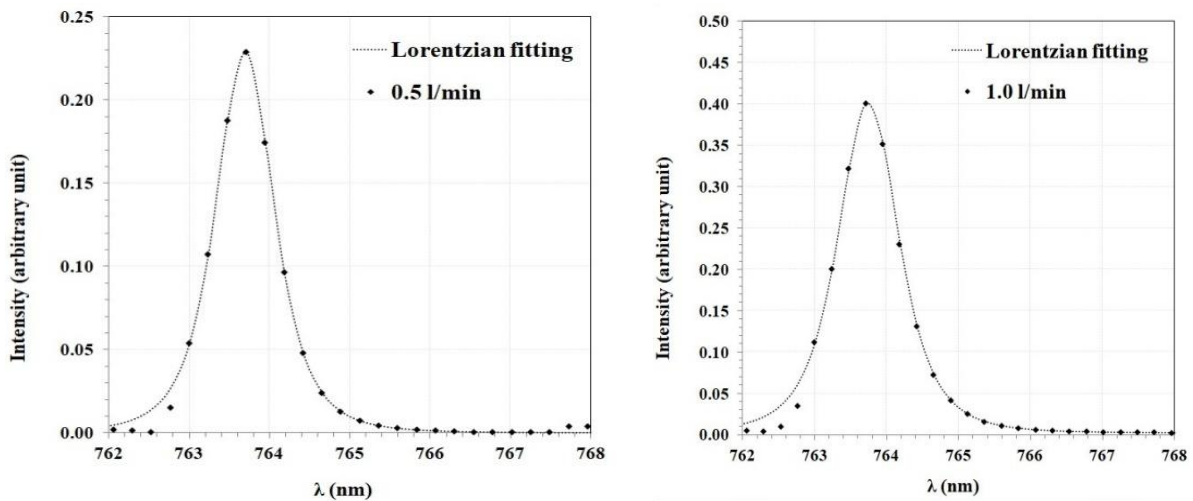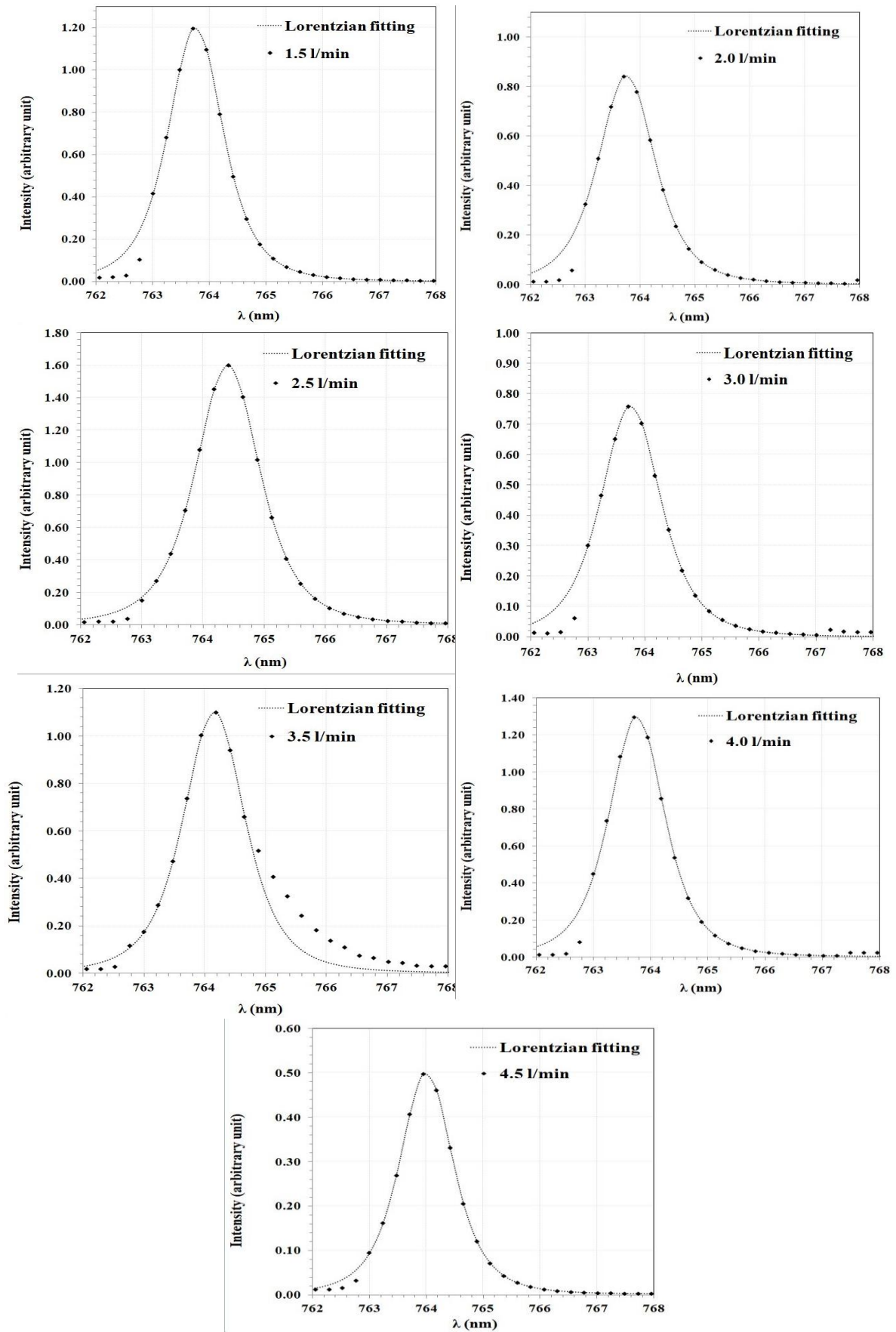Figure 5 shows Boltzmann plots for different Ar gas flow rates.

Figure 5: Boltzmann plots for the different Ar gas flow rates.

Using Stark-Broadening, Equation 2, and Lorenz Fitting, n_e for the line (746nm) was calculated:

$$n_e = \frac{\Delta\lambda}{2W} Nr \qquad (2)$$

Figure 6 shows (n_e) for the different Ar gas flow rates.

Figure 6: Stark-Broadening and Lorentzian fitting for the line 746nm for different Ar gas flow rates.

Figure 7 shows the relationship between electron temperature and electron density as a function of gas flow rate. It is noted from the figure that n_e decreases with the flow rate until a flow of (2.5 l\m), where it strated to increase with the increase of the gas flow rate; on the other hand, T_e was noted to decrease with the increase of the gas flow rate. This decrease is due to the ionization decrease and the increase in the number of collisions between particles.
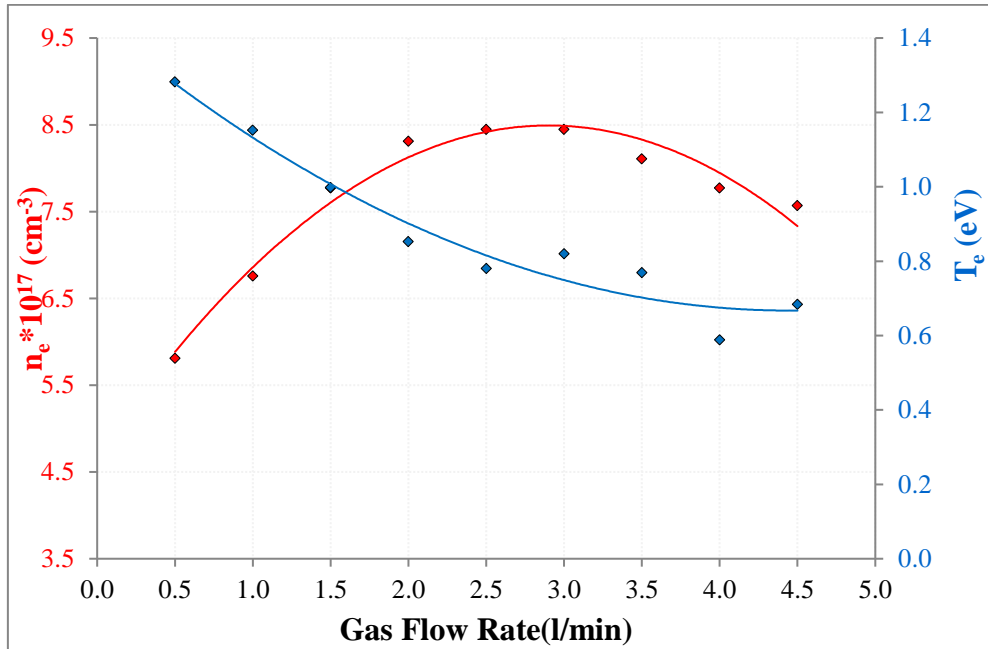
Figure 7: The relationship between electron temperature and electron density as a function of gas flow rate

4-3- Debye length:-

Plasma frequency, f_p, is calculated from Equation 3:

$$f_p = 2\pi \times 9\sqrt{n_e} \tag{3}$$

Where: $\boldsymbol{\lambda}_D$ represents the Debye length and is calculated from Equation 4:

$$\boldsymbol{\lambda}_D = 1.38 \times 10^6 \frac{T_e^{3/2}}{n_e^{1/2}} \tag{4}$$

Figure 8 represents the relationship between plasma frequency , Debye length as a function of gas flow rate. f_e increases because it depends on the density of electrons. f_e and $\boldsymbol{\lambda}_D$ depend on n_e as described by Equations 3 and 4.
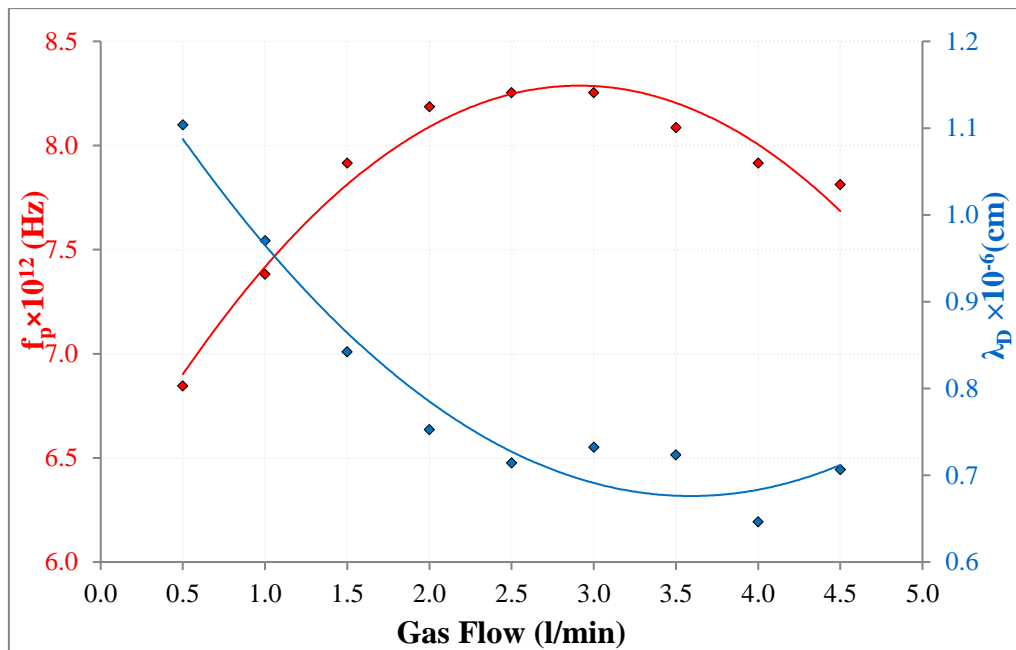
Figure 8: The relationship between plasma frequency and Debye length as a function of flow rate

Table 1: **The values of e**lectron temperature T_e and electron density n_e, Debye length λ_D, and plasma frequency f_b as a function of Ar gas flow rate.

Flow (L/min)	Te (eV)	FWHM (nm)	n_e*10^{17} (cm^{-3})	f_p (Hz) $*10^{12}$	λ_D $*10^{-6}$ (cm)
0.5	1.282	0.860	5.811	6.845	1.104
1.0	1.152	1.000	6.757	7.382	0.970
1.5	0.998	1.150	7.770	7.916	0.842
2.0	0.853	1.230	8.311	8.186	0.753
2.5	0.780	1.250	8.446	8.253	0.714
3.0	0.820	1.250	8.446	8.253	0.732
3.5	0.769	1.200	8.108	8.086	0.724
4.0	0.588	1.150	7.770	7.916	0.646
4.5	0.684	1.120	7.568	7.812	0.707

5-3- The working gas temperature:

The temperature of the non-thermal pressure plasma gas was measured under atmospheric pressure using a thermometer by shedding the plasma on a thin piece of silicon placed under the plasma torch.The thin piece of silicon was exposed to plasma for different times (5, 10, 15 minutes). A slight increase in plasma temperature was observed at constant flow rate of (2.5 l/min) as shown in the Table 2.

**Table 2:** The working gas temperature values as a function of time at a constant gas flow rate of (2.5l\min).

Time(min)	Temperature(^{0}C)

5	16
10	17
15	18

Table 2 shows the working gas temperature values as a function of time at a constant gas flow rate of (2.5 l/min). From the table, it is noted that temperature increases slightly but it remains within the range of the laboratory temperature. The limits that qualify a system for medical use if the criteria for cold plasma has been met.

6-3-The length of the plasma jet:

It is good and important to know and understand the factors that control the length of a plasma jet to find the benefits of the practical use of a plasma torch. Examining and measuring the effect of the flow rate of the argon gas, the length of the plasma jet is controlled. Figure 9 shows the effect of the argon gas flow rate on the length of the plasma jet. It was observed that the length of the plasma jet increased with the increase of the flow rate and it was noted that the flow rate (2.5 l\min) gave the longest length of the plasma jet.
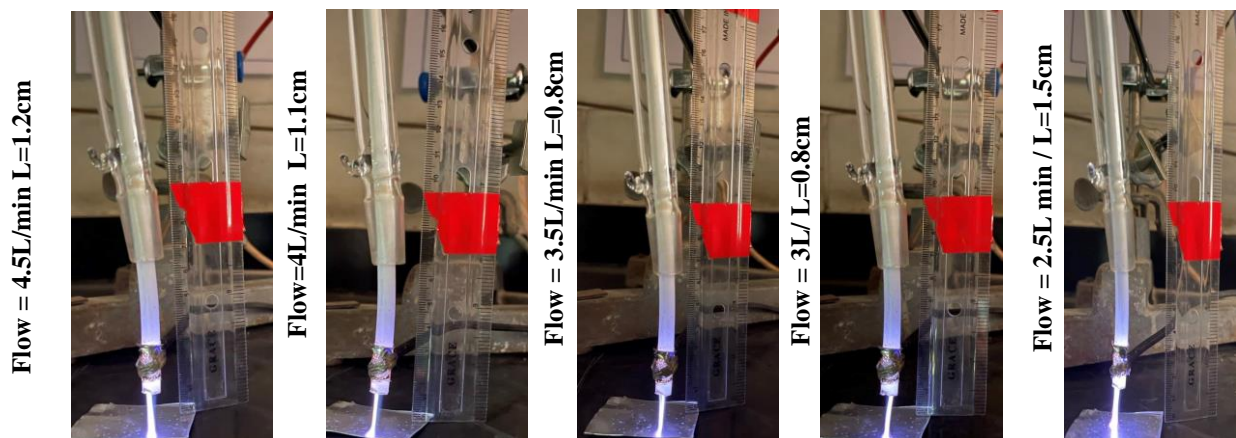
Figure 9: Plasma jet length as related to the gas flow rate.

4-Conclusions

A plasma jet system was built and characterized electrically, spectroscopically, and thermally. From the spectra, the plasma parameters (T_e) and (n_e) were calculated as a function of gas flow rate , and it was found that the relationship between (T_e) and (n_e) is inverse, (T_e) decreased from (1.282) to (0.684), and (ne) increases from (5.811) to (7.568) with the increase of the gas flow rate. This shows that the plasma parameters change with the gas flow rate, and this is consistent with previous research[11][12][13]. The length of the plasma jet was determined as a function of gas flow rate. It was also found that the best length was at a flow rate of (2.5 l/m). The associated gas temperature was measured, and it was found that this temperature is less than or within the limits of room temperature. When changing the time used to generate plasma, it gave an initial temperature of 16^0C, and when increasing the time used, the temperature increased slightly, amounting to 18^0C, and this indicates the stability of the temperature. The temperature of the generated plasma system indicates that we can use it effectively in biological application, in addition to that, when argon gas flow rate was (2.5 l\m) the length of the plasma jet reached (1.5cm), and when the gas flow increased, the length of the plasma torch decreased a little (0.8cm) and then returned to stability at (1.2cm). This also indicates the stability of the plasma torch, which is useful biological applications. Figure (3) represents the spectrum produced by the plasma torch after its diagnosis, Hydroxide molecules, free radicals of oxygen and nitrogen gas, and ionic and molecular nitrogen are all part of the

plasma torch's output spectrum after it has been properly diagnosed. All these specifics are helpful in the elimination or treatment of viruses. and the length of the torch leads to greater flexibility in work through which it is possible to transfer the plasma for a longer distance and this flexibility leads to a better performance. From the results of this research, it is concluded that it it is possibile to build plasma system suitable for biological applications.

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