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Investigation of Argon Plasma Jet Characteristics and the Influence of Gas Flow Rate on Plasma Emission Parameters using Bronze Alloy

Sarah Faris Khaleel, Kadhim A. Aadim*
Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq

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Abstract

This study analyses the physical and optical properties of jet plasma at atmospheric pressure (APPJ) using optical emission spectroscopy (OES), focusing on the effect of argon gas flow rate. The results show that increasing the gas flow rate from 2 to 4 litres/minute results in an increase in the spectral emission intensity due to increased ionisation within the plasma. Using the Boltzmann method, it was noted that the electron temperature decreased from 0.609 to 0.526 electron volts, while the electron density increased as the gas flow rate was increased. This reflects an altered relationship between ionisation and energy loss. With higher gas flow, the plasma becomes more concentrated, but its temperature decreases. In this case, it becomes more manageable, ideal for advanced use.

Keywords: Optical Emission Spectroscopy, Atmospheric Plasma Jet, Plasma parameters, Bronze Alloy, Electron Temperature

دراسة خصائص بلازما النفث للأرجون وتأثير تدفق الغاز على معلمات انبعاث البلازما باستخدام سبيكة البرونز

ساره فارس خليل*, كاظم عبد الواحد عادم
قسم الفيزياء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

تتناول هذه الدراسة الخواص الفيزيائية والبصرية لنفث البلازما عند الضغط الجوي (APPJ) باستخدام تحليل الطيف البصري للانبعاث (OES)، مع التركيز على تأثير معدل تدفق غاز الأرجون. أظهرت النتائج أن زيادة معدل تدفق الغاز من 2 إلى 4 لتر/دقيقة تؤدي إلى زيادة شدة الانبعاث الطيفي نتيجةً لزيادة التأين داخل البلازما. وباستخدام طريقة بولتزمان، لوحظ أن درجة حرارة الإلكترونات انخفضت من 0.609 إلى 0.526 إلكترون فولت، في حين ازدادت كثافة الإلكترونات مع زيادة معدل تدفق الغاز. يشير ذلك إلى تغيّر في التوازن بين عمليتي التأين وفقدان الطاقة. ومع زيادة معدل تدفق الغاز، تصبح البلازما أكثر كثافة، لكن درجة حرارتها تنخفض. وفي هذه الحالة، يمكن التحكم بها بسهولة، خصوصًا عند استخدامها في التطبيقات المتقدمة.

*Email: kadhim.aadim@sc.uobaghdad.edu.iq

1. Introduction

Atmospheric pressure plasma (APP) is a emerging technique that has increasingly gained interest of researchers. It has wide-ranging uses in areas like medicine, the industry, and environment, notably in sterilization, surface modification, and tissue treatment. Among the various plasma generation techniques, atmospheric pressure plasma jet (APPJ) is one of the most commonly used, due to its simplicity in operation, lack of need for complex equipment, and its ability to generate stable plasma stream even in open environments [1, 2].

Some recent studies looked at the features of atmospheric pressure plasma jets. For example, Giannakaris et al. (2023) conducted a study on argon-based plasma generated using industrial jet devices. They measured how hot the electrons were in various working setups, using optical emission tests [3]. Bedrouni et al. (2023) looked into what happens when methane was added to argon plasma and the consequent changes in the jet properties, focusing on the jet length and spectral emission intensity using optical emission method [4]. Also, Giannakaris et al. (2025) applied OES and LIBS methods to investigate how plasma jetting influences surface cleaning, and to see what chemical reactions happen because of that [5].

Despite the extensive research conducted in this field, most of the works used either ready-made or very advanced systems. The basic systems made locally are still being tried or tested. In particular, the relationship between gas flow rate and plasma properties in this type of device was not fully looked into yet, especially when the configuration adopted is as basic as the one currently used.

As part of this research, a low-cost, locally manufactured plasma jet system was designed, based on a two-electrode configuration. One electrode is a metal needle from which argon gas is ejected and connected to a high-voltage (DC) power source, while the second electrode is made of a bronze alloy. Plasma is generated in the air between the electrodes once the voltage is applied, appearing as a constant visible glow.
OES was employed to track changes in the optical and electronic properties of the resulting plasma when the argon gas flow was changed.

The aim of the study was to measure the electron temperature (T_e) and electron density (n_e), and to analyse the ionisation behaviour and energy distribution within the jet at different argon gas flow rates. It attempts to fill the information gap in the performance of local APPJ systems and to provide experimental data that supports design improvement and expanded use in the fields of environment and medicine.

2. Theoretical Consideration

Atmospheric pressure plasma jet (APPJ) is a cold plasma generated when a strong electric field is applied using noble gases such as argon or helium [6]. The physical mechanism for generating this type of plasma is established on ionization processes, which occurs from collisions between free electrons and gas atoms in the presence of an applied electric field [7, 8]. When a sufficient potential difference is applied between two electrodes and a gas at atmospheric pressure is present between them, the few electrons in the gas begin to absorb energy from the electric field, accelerating and colliding with the gas atoms. These collisions lead to the direct excitation or ionisation of the atoms, releasing new electrons and positive ions. These collisions, known as avalanche ionisation, are repeated in series until a complete electrical discharge is formed, resulting in the formation of plasma. This plasma is characterised by being non-thermal, as the electrons have high energy (several electron volts), while the temperature of the ions and gas remains relatively low. Plasma emits characteristic optical radiation, produced by electronic transitions. This radiation can be analysed by spectroscopy, through the emission lines coming from excited atoms or ions [9, 10].

Optical emission spectroscopy (OES) is one of the most commonly used techniques to characterize non-thermal plasmas, particularly at atmospheric pressure [11]. It is a non-intrusive method that enables the evaluation of plasma properties through the radiation emitted. This technique relies on analysing the photons produced by the transition of excited atoms or ions to lower energy levels. The resulting radiation appears as characteristic spectral lines, from which the plasma composition and physical parameters can be inferred [12]. OES is particularly used to evaluate the electron temperature (Te) using the Boltzmann method and the electron density (ne) by analysing the spectral line broadening according to the Stark effect.

2.1 Electron Temperature (T_e)

Electron temperature (T_e) (in eV) is one of the essential variables used to evaluate the properties of plasma. It is estimated using the Boltzmann method according to the following equation:

$$\ln\left[\frac{\lambda_{ji} I_{ji}}{hcA_{ji} g_j}\right] = \frac{1}{\mathrm{k_B T}}(E_j) + \ln\left[\frac{\mathrm{N}}{\mathrm{U(T)}}\right] \quad (1)$$

Here, I_{ji} represents the relative intensity of the emission line between energy levels i and j, g_j is the multiplicity factor or statistical weight of the higher level emitted during the transition, λ_{ji} is the wavelength (in nano meters), E_j is the excitation energy (in electron volts) of the j_{th} level, A_{ji} is the probability of spontaneous transition of radiation from level i to the lower-level j, N denotes the population density of the energy state, and K_B represents the Boltzmann constant [13].

2.2 Electron Density (n_e)

To calculate the electron number density(n_e), FWHM and Lorentzian fitting were employed, according to the following equation:

$$n_e = \left(\frac{\Delta\lambda_{FWHM}}{2w}\right) N_r \quad (2)$$

Here, Δλ (FWHM) represents the Full Width at Half Maximum of the spectral line, and ω is the theoretical full width of the Stark line, which is calculated for the same reference electron density. For neutral atoms, the reference density is Nr ≈ 10^{16} cm^{-3}, and for single charged ions, it is Nr ≈ 10^{17} cm^{-3} [14].

2.3 Plasma Frequency (ω_p):

Plasma frequency is defined as the factor that determines which disturbances in the quasi-neutral equilibrium state within the plasma generate electric fields. As a function of plasma density, this frequency plays a vital role in determining its essential properties. Because of the small value of electron mass (m_e), plasma frequency is generally quite elevated, and is calculated using the following equation:

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

Where ε_0, n_e, e, and m_e represent the permittivity of free space, electron concentration, fundamental charge, and electron mass, respectively [15].

2.4 Debye Length (λ_D):

The Debye length of an electron (λ_D) (in meters) is the maximum microscopic distance for charge separation in plasma. It defines the spatial extent of the plasma sheath or its protective boundary, and is calculated using the following equation [15]:

$$\lambda_D = \sqrt{\left(\frac{\epsilon_0 \mathbf{k}_B T_e}{n_e e^2}\right)} = 7430 * \sqrt{\frac{T_e}{n_e}} \quad (4)$$

2.5 Plasma Parameter (N_D:)

Plasma parameter (N_D) denotes the number of particles within a Debye sphere, or a sphere of radius equal to Debye length (λ_D). It is calculated using the equation [16]:

$$N_D = \frac{4}{3}\pi n_e \lambda_D^3 \quad (5)$$

3. Experimental Part

The experiment was carried out using a cold plasma jet system at atmospheric pressure, designed in a two-electrode configuration using locally manufactured components. The first electrode is a hollow metal tube with an inner diameter of 3 mm, which serves as the cathode (negative electrode) directly connected to the 20 kV terminal of a high-voltage DC voltage source. The tube is like a thin needle to push the argon gas flow concentrically toward the discharge point. This focuses the electric field at the end of the tube, creating ideal conditions to initiate ionisation and making a stable plasma jet.

The other electrode is a bronze metal sheet (80% Cu and 20% Sn) with a purity of 99.99%. It is manually formed into an S-shaped inclined plane, giving it a multidirectional curved surface. This shape helps the electric field to spread better, which keeps the plasma jet stable at the tip. The plate was placed inside a small beaker containing approximately 10 ml of distilled water, submerged to a depth of 5 cm, to ensure consistent electrical contact and continuous cooling during the discharge.

The tube nozzle (cathode) was positioned 1.5 cm above the water surface, and pure argon gas was passed through it at variable rates of 2, 2.5, 3, 3.5, and 4 litres/minute using a micro-flow regulator. A constant operating voltage of 20 kV was maintained using a direct current source, which generated an electrical discharge in the gap between the needle and the water surface, thereby ionising the argon and forming a distinct plasma jet extending toward the anode.

The radiation emitted by the plasma was recorded using a high-resolution optical spectrometer operating in the spectral range from 170 to 1100 nanometers. The optical fiber was positioned at a constant distance from the nozzle exit, and a single measurement point was selected to ensure stable and uniform recording conditions. Each spectrum was monitored for one minute at each flow rate after the jet stabilised to ensure accurate comparison between readings.

The spectral data were processed using OriginPro software, where spectral peaks were manually identified, and a graph was generated based on the logarithmic relationship of the Boltzmann equation. The electron temperature was calculated from the slope of this graph.

The electron density was estimated by analysing the full-wavelength spectral line broadening at half-maximum (FWHM) after performing a precise Lorentzian fit to each spectral line. These data were used to derive the necessary values for the plasma's electronic properties. It is worth mentioning that the APPJ setup used in this study is simple, as shown in Figure 1.

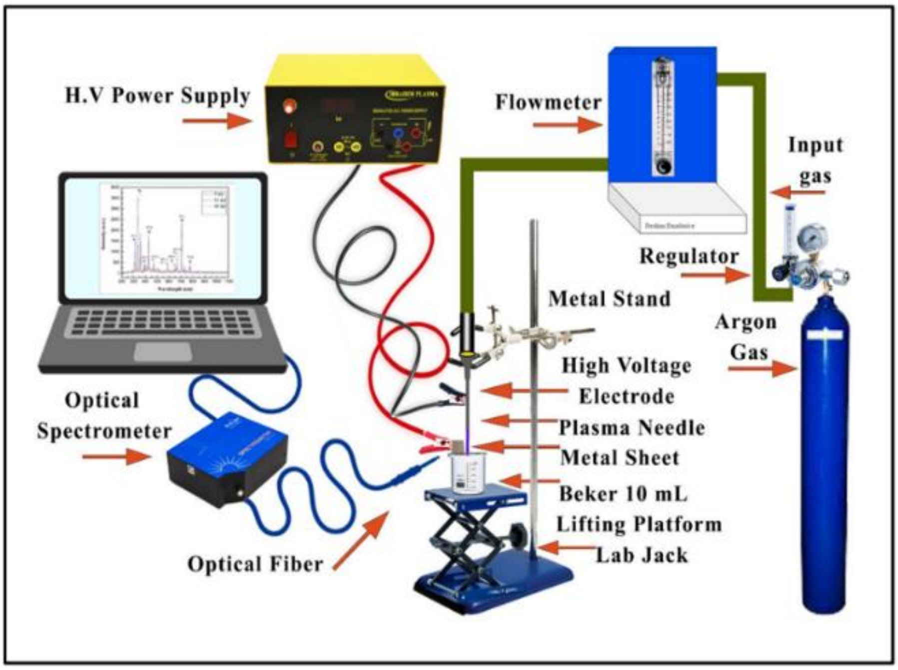

Figure 1: A schematic diagram of atmospheric non-thermal plasma jet system, including all tools and PC control of the spectrometer equipment.

4. Results and Discussion

The plasma jet generated at atmospheric pressure is divided into three main regions where electrical discharges are observed. First, it begins within the jet source itself, where the discharge is generated inside the chamber where the gas is ionised. This is followed by a discharge at the outlet nozzle, where the ionised gas is released into the surrounding air. Finally, the discharge occurs at the target surface (such as a liquid), where additional electrical and chemical reactions occur, leading to secondary ionisation of the exposed surface. The spectral emissions of the generated plasma were recorded using a plasma jet system at atmospheric pressure, with varying argon gas flow rates. After data collection, the spectrum distribution was plotted by plotting the signal amplitude versus wavelengths, using optical emission spectroscopy (OES) to record the emission spectra of cold plasma generated from argon gas.

The spectrum contained spectral lines characteristic of argon atoms and ions, reflecting the presence of multiple excited states resulting from electron collisions within the plasma. Figure 2 shows the shapes of the plasma jet when the gas flow rates ranged between 2 and 4 L/min clearly demonstrating the effect of this change on plasma properties, such as density and the formation of active species. This happens because the electrons hit gas atoms more often when the gas is going faster. This leads to a redistribution of energy within the plasma, directly influencing the level of ionization as well as photon emission. This agrees with the results of Hashem et al. (2017) [17], whose study showed that increasing argon flow led to a significant increase in electron density due to increased collisions in the jet region. They also observed a gradual decrease in electron temperature due to energy loss in inelastic collisions. These results support the findings of Zaplotnik et al. (2021) [18], who showed that changes in the shape of the plasma jet and the intensity of the spectral emission are directly related to the balance of ionisation and excitation within the discharge region, especially when the operating conditions, such as the gas type and its flow rate, change. The consistency of the current results with previous studies, despite the simplicity of the locally used design, enhances the reliability of the experimental performance and highlights the system's efficiency in generating stable plasma amenable to accurate spectroscopic diagnosis.

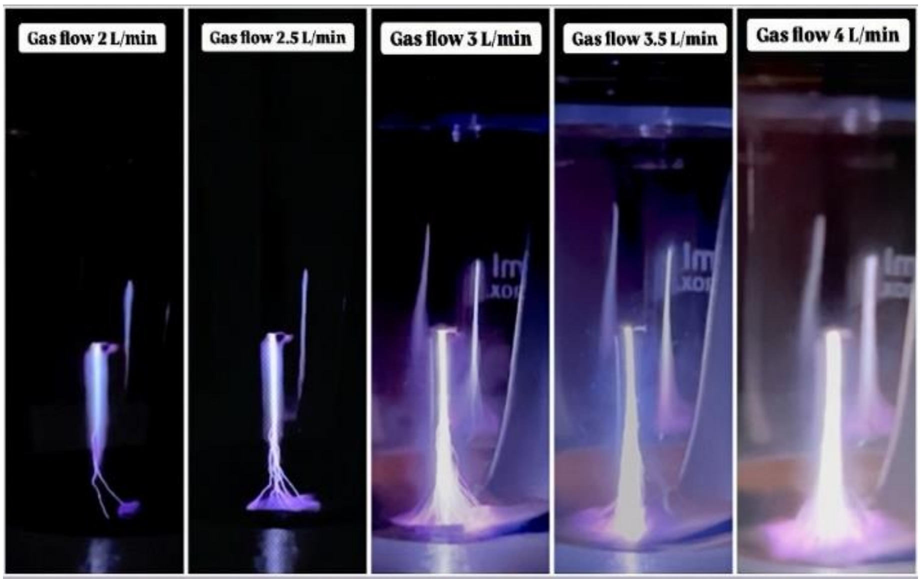

Figure 2: Argon plasma shape generated at different gas flow rates (2-4 l/min).

As shown in Figure 3, the spectral emission was recorded over a range of 170 to 1100 nm at various argon gas flow rates ranging from 2 to 4 litres/minute. The spectra showed clear agreement with the standard lines attributed to both Ar I and Ar II, reflecting the presence of active excited and ionised states within the resulting plasma. The figure shows that the intensity of the spectral lines gradually increases with increasing gas flow rate. This behaviour can be explained physically by the fact that the increased amount of gas passing through the plasma needle leads to an increase in the number of neutral atoms and thus an increased probability of collisions between electrons and these atoms within the discharge region. These collisions result in the excitation of a larger number of atoms, which translates into an apparent increase in the intensity of the spectral emission peaks. These results are consistent with those reported by Abood et al. (2022) and Ahmed and Humud (2024) [19, 20], whose studies showed that increasing the argon gas flow rate led to higher spectral line intensity and electron density, resulting from increased collisions and the ionisation of a greater number of atoms within the plasma. This consistency reflects the reliability of the physical performance of the system used in this study.

As shown in Figure 3, distinct spectral peaks for nitrogen molecule (N_2) were observed within the range 308.51 nm to 404.81570 nm, including 308.51, 336.64240, 357.50290, 380.65930, and 404.81570 nm. In addition, the spectrum contains clear peaks attributed to atomic argon (Ar I) within the range 671.92 to 965.77 nm, along with some small peaks for copper (Cu) elements, such as Cu II at 283.73 nm, Cu I at 296.12 nm, and Cu II at 653.00 nm. The results showed that a continuous increase in the argon gas flow rate led to a significant increase in the spectral emission intensity. The reason for this increase is the abundance of argon particles within the plasma, which increases the chance of collisions between electrons and gas atoms, resulting in more ionisations and excitations, thus increasing the amount of energy released as light. Increased gas flow helps distribute energy better within the plasma, making interactions between electrons and ions more efficient. This is reflected in the appearance of clearer and stronger spectral peaks.

The intensity of the emission, particularly the argon peaks (its atoms and ions), shows that ionisation increased with increased gas flow rate. This is because the more particles there are, the more collisions with electrons occur, resulting in greater excitation, resulting in higher-energy photons. With improved energy distribution, electrons can reach higher energy levels, resulting in stronger spectral emission at specific wavelengths. The clarity of these spectral peaks and their distribution within known ranges supports the accuracy of the spectral diagnosis, indicating the stability and efficiency of the resulting plasma under approved operating conditions.

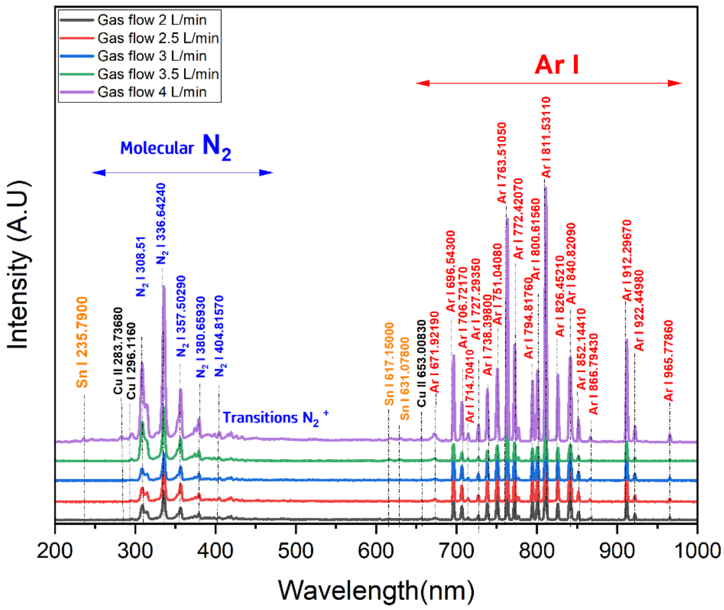

Figure 3: The plasma emission spectra of bronze alloy at various argon gas flow rates (2-4) l/min and constant applied DC voltage of 20 kV.

Using the Boltzmann diagram method and Equation (1), the plasma electron temperature was determined. In the case of argon-emitting plasmas, four ion or atomic spectral lines were applied using this method. Operating with a direct current (DC) source and at various argon gas flow rates ranging from 2 to 4 L/min, the electron temperature (T_e) was calculated by plotting (λ_{ji} I_{ji} / g_j A_{ji}) on the vertical axis against the excitation energy E_j in electron volts on the horizontal axis, as shown in Figure 4. All the graphs showed clear straight lines, with approximately the same slope ($-1/k_BT_e$) when the line was fitted linearly, enabling the temperature to be derived with high accuracy.

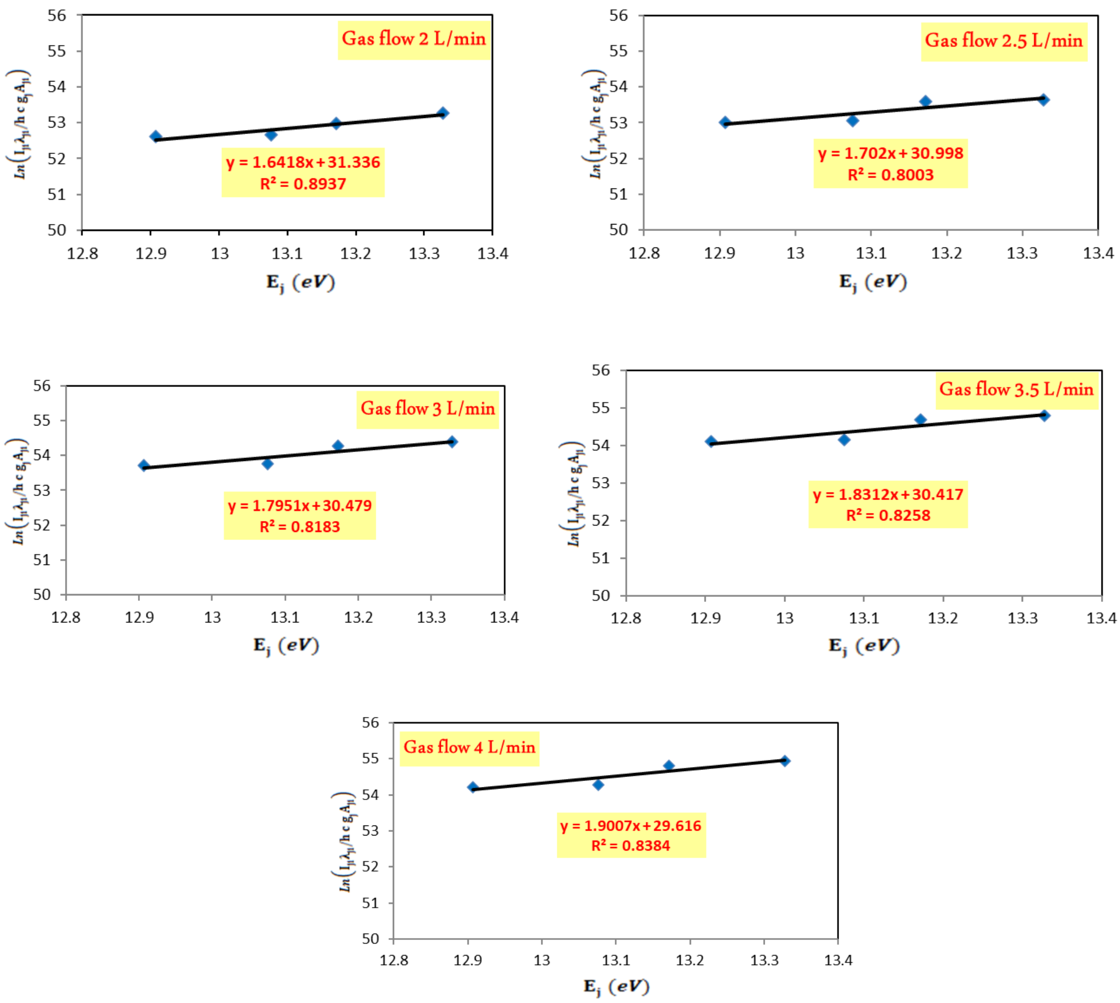

Figure 4: Boltzmann plots for Ar plasma using linear fitting at different gas flow rates (2-4) l/min and a fixed applied DC voltage of 20 kV.

The electron temperatures (T_e) in the argon plasma calculated for various gas flow rates ranging from 2 to 4 litres/minute and a constant voltage of 20 kilovolts using direct current (DC) were derived from the slopes of the graphs in the previous figures. Figure 5 shows the change in the electron temperature in the argon plasma at these gas flow rates. The results showed that the value of (T_e) ranged between 0.609 and 0.526 eV, which corresponds to specific electron temperatures when converted to Kelvin. It was observed that increasing the gas flow rate led to a gradual decrease in the electron temperature. This decrease can be explained by the fact that increasing the gas flow contributes to an increase in the number of molecules and atoms within the discharge region, leading to a higher rate of inelastic collisions with electrons. These collisions result in a loss of electron energy, thus lowering their temperature. These interactions also contribute to increased heat loss within the plasma, which indirectly enhances the electron cooling process. These results are consistent with two previous studies [13, 21], where it was observed that increased gas flow rate led to a decrease in electron temperature due to increased collisions and energy loss within the plasma.

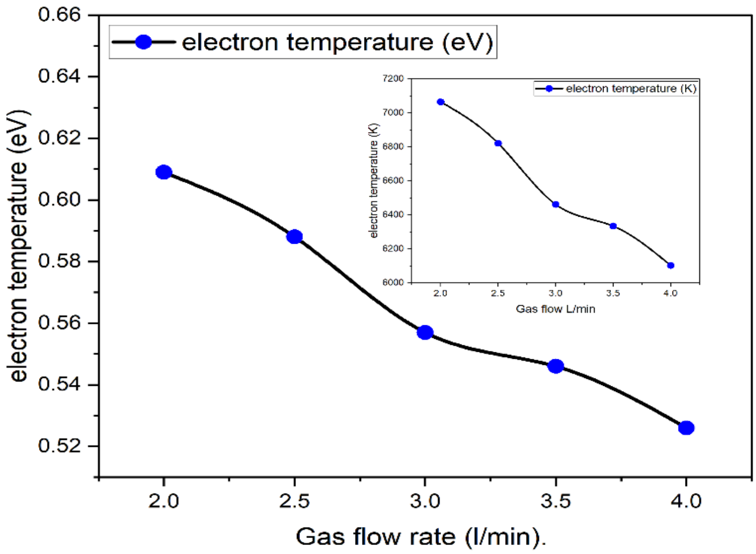

Figure 5: Argon plasma electron temperature with gas flow rates varying between (2-4) l/min.

As shown in Figure 6, the intensity of the plasma jet increases with increasing gas flow rate, indicating a rise in plasma density, which is equivalent to an increase in the number of ions and ionised molecules. This increase leads to enhanced interactions between electrons and ions within the plasma, resulting in the broadening of spectral lines. The higher the density, the stronger the interactions, which disturb the energy levels of the atoms and lead to irregular broadening of the spectral lines. In addition, increasing gas flow leads to a rise in ion density and thus increased Stark effects, which contribute to significant line broadening. Table 1 shows the values of the electron temperature with increasing argon gas flow rate at DC current. The results showed that all values gradually decreased with increasing flow rate, which is consistent with the results of Michel et al. [22].

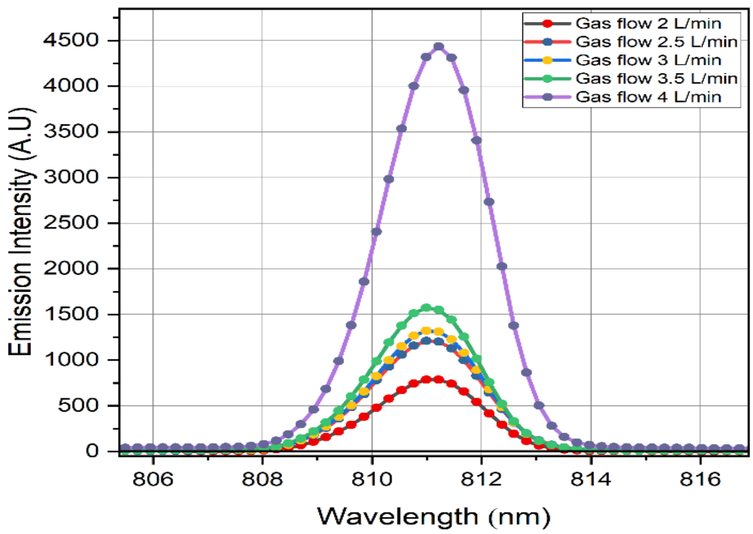

Figure -6: Stark-broadened argon emission line in the range 808–814 nm. A Lorentzian curve fitting was applied to determine the full width at half maximum (FWHM) for electron density estimation.

Table 1: Plasma jet parameters.

Gas flow L/min	FWHM (nm)	Te (eV)	ne (cm^{-3})	f_p (Hz)	λ_D (cm)	N_D
2	2.26	0.609	1.38E+16	1.053E+12	4.94513E-06	6.965035343
2.5	2.30	0.588	1.40E+16	1.06228E+12	4.81446E-06	6.541158451
3	2.31	0.557	1.41E+16	1.06458E+12	4.6778E-06	6.025858936
3.5	2.33	0.546	1.42E+16	1.06918E+12	4.61154E-06	5.823395561
4	2.37	0.526	1.44E+16	1.07832E+12	4.48808E-06	5.460260793

Figure 7 shows how variations in argon flow rate influence electron temperature and electron density. The results showed that as the gas flow rate increased from 2 to 4 litres/minute, the electron temperature gradually decreased, while the electron density increased significantly. This behaviour can be explained by the fact that increasing the gas quantity contributes to plasma cooling due to increased collisions between electrons and neutral molecules, leading to inelastic energy loss from the electrons and, consequently, a decrease in their temperature. On the other hand, as the number of ionisable gas molecules increases, the number of electrons produced by collisions also increases. This results in a significant increase in electron density in the plasma. This increase reflects the balance between two fundamental processes in the jet: ionization, on the one hand, and cooling, on the other. Actually, when the gas flow gets higher, collisions become more frequent, so the ionization gets stronger. However, energy lost due to inelastic collisions also increases, leading to a slight drop in temperature. After that, the plasma turns thicker and cooler, reaching a stable state suitable for high-precision applications.

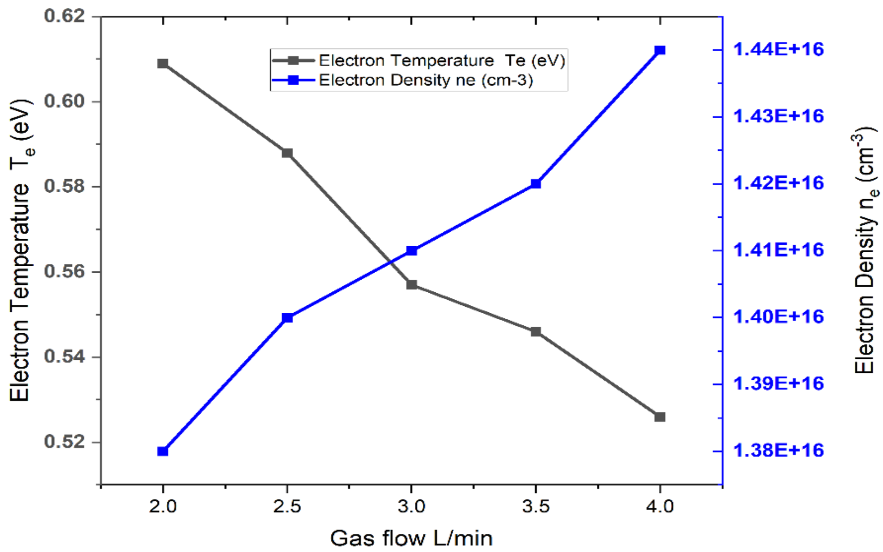

Figure 7: Temperature and electron density at various gas flow speeds.

5. Conclusion

The study showed clearly that increasing the argon gas flow rate using a plasma jet at normal pressure directly influences the spectral and electronic properties of the plasma. It was noticed that when flow is high, the plasma gets more excited and ionised, and increasing the plasma glow, showing clear spectral lines from argon gas and its ions. The results also showed that the electron temperature progressively decreased with increasing flow rate, because of non-elastic hits and energy getting lost, while the electron density increases significantly, a consequence of more intense ionisation. The analysis revealed that the brightness of the lines increases when plasma is denser, indicating a clear change in the energy level distribution. These data highlight the balance between ionisation and cooling within plasma jets and confirm that changing how fast gas goes is a good way to control plasma behavior for different uses according to application needs.

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Competing interests The authors have not disclosed any competition of interest.
Ethical Approval The writers want to state that they have no conflicts of interest.

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