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Spectroscopic Diagnostic of Silicon Plasma Produced by DC and AC Plasma Jet Techniques: Comparative Study

In this work, modern technologies use plasma jets in industrial and medical applications for their exciting effectiveness, the properties of which are determined by the type of gas and metal placed as electrodes in the system, as they operate under atmospheric pressure and generate cold plasma, and by using silicon metal and argon gas connected to a high voltage power supply, the current was changed to generate plasma and characterize the produced optical spectrum and compare the effect of this change on its parameters (temperature and electron density) and know the processes associated with its generation. With an applied voltage of 11 kV and using optical emission spectroscopy (OES), the spectral diagnostics were recorded to describe the resulting plasmonic properties. Using DC current, the peak spectral density shown by the results was higher than the alternating current. By comparing the effect of the type of current for the same gas and silicon metal on the parameters, it was found that the values of temperature and electron density at direct current were 2.22-2.67 eV, 3.238×10^{16}-3.305×10^{16} cm^{-3}, at a gas flow rate of 0.5-2 L/min. At the same flow rate and by applying AC current, it was found that the temperature and electron density were 1.018-1.093 eV, 5.026×10^{16}-6.897×10^{16} cm^{-3}. Through the comparative study, the effect of direct current was greater on the plasma parameters than alternating current, since alternating current works in the form of an intermittent sinusoidal pulse that affects the movement of charges and thus causes a momentary interruption in the generation of plasma, which leads to cooling the plasma column and reducing the electron density.

***Keywords*:** Plasma jet; Plasma parameters; OES; AC plasma; DC plasma
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1. Introduction

The widespread interest in atmospheric pressure plasma technology is increasing excitingly in plasma physics applications [1]. Low-temperature plasma jets are unique plasma products that can move plasma away from electrode constraints and out of gas enclosures and chambers [2]. For example, it inhibits bacteria, whitens teeth and regenerates tissues in the medical field [3]. As for the industrial field, there are many examples of its importance, such as coatings, paints, and other wide applications [4]. The plasma jet is one of several types of plasma production, including laser energy [5-7], which is called laser-induced plasma, microwave-produced plasma, and others [8]. This plasma gains its importance from the fact that its electrons have a high temperature, which enables them to transfer energy to the levels of ionization, activation, and even the disintegration of molecules, even though the collisions are flexible (although in an elastic collision, no energy transfer occurs) [9]. Plasma contains small charged particles that are free and not bound to each other [10]. Unlike these charges, the lower energy particles outside the plasma are not capable of breaking the bonds of the group of charged particles inside the plasma cloud due to the presence of electric and magnetic fields that force the plasma cloud to remain cohesive to maintain itself according to the property of the collective behavior of the plasma [11]. Because knowledge of plasma parameters is necessary to understand its behavior, diagnostic methods are essential for this. One of the modern methods is optical emission spectroscopy technology, which senses the behavior of photons generated by electricity and analyzes its emissions using the optical spectrum [12] and relies on calculating the ray emitted as a result of the process of excitation, ionization, and energy transfer of the plasma [13].

Electron temperature is an important thermodynamic parameter when generating plasma, as it can predict particle aggregates with different velocities, relative energy levels and their distribution [14,15]. The temperature of the electrons locally is calculated from the equation [16]:

$$\ln\left[\frac{\lambda_{ji}I_{ji}}{hcA_{ji}g_i}\right] = -\frac{1}{kT}\left(E_j\right) + \ln\left[\frac{N}{U(T)}\right] \qquad (1)$$

where λ is the wavelength, I_{ji} is the intensity, A_{ji} is the probability of transition, g is the statistical weight, E is the energy of the excited state in eV, N is the population density of the state, and k is the Boltzmann constant

As for the electron density, the linear Stark spectral line broadening method is considered a way to measure it. Directly responsible for the spectral line broadening of the plasma that depends on the electron temperature and the mass of the atom emitters is the Stark and Doppler width effect [17]. Depending on their energy and density, adjacent charged plasma particles produce a Stark expansion, which is a function of nearby electric fields [18]. Stark is important in determining the density of plasma electrons at a certain temperature after analyzing it spectroscopically [19]. From this, we can calculate the electron density from the equation [11]:

$$n_e = \left[\frac{\Delta\lambda}{2\omega_s}\right] N_r \qquad (\mathrm{cm}^{-3}) \qquad (2)$$

where, $\Delta\lambda$ is the full width at half maximum (FWHM) nm, ω_S is the broadening parameter of Stark, and N_r is the reference density of electrons

This research aims to find a comparison of describing the parameters of argon plasma using silicon metal in a non-thermal jet plasma system when changing the type of current used (direct and alternating) and studying the effect of changing it and the gas flow rate on the behavior of the resulting plasma through the interaction of charged particles and increasing the ionization, excitation and collision processes using the OES method and the Boltzmann diagram.

2. Experimental Part

The plasma jet system was installed under atmospheric pressure conditions. A DC and AC power supply with a 20 kV maximum voltage and 50 kHz frequency was used. A tube to pump argon gas from a cylinder was connected to a gas flowmeter with a ratio of 1-5 L/min with a three mm outer diameter stainless steel needle, which was attached to the high-voltage power supply's cathode. The anode electrode was connected to silicon metal immersed 2 cm from it in a beaker 10 mm containing non-ionic water placed below the end of the plasma jet needle. A S3000-UV-NIR spectrometer was used and connected to the system to record diagnostic data for 0.5-2 L/min flow rates. The spectrum was recorded within 200-1000 nm directly from the plasma jet. Data were compared and examined with the reported data from the National Institute of Technology and Standards (NIST). Using Boltzmann's equations and plots, the parameters were calculated and the plasma properties of silicon metal plasma were discussed.

3. Result and discussion

Figure (1) shows the intensity of the plasma spectra obtained by OES at an applied voltage of 11 kV, frequency of 50 kHz, for argon flow rates of 0.5-2 L/min when used DC voltage. The spectral peaks appeared mainly in the wavelength range 200-1000 nm and were compared with the global database (NIST) [19]. The highest peak in the diagnostic process of the argon gas spectrum was recorded at the wavelength 335.28 nm, and some spectral peaks appeared for nitrogen at 356.33 and 420.34 nm. As a result of the increase in the gas flow rate, the increase in the emission process was evident as a result of the increase in the ionization process of gas atoms in the plasma column [18]. The spectrum shows three peaks for Si^{2+} at 386.19, 403.71, and 625.93 nm and the highest at 403.71 nm, which was recorded after comparing it with the NIST database. An increase in peak height appears when the flow rate exceeds 0.5 L/min. Figure (2) shows the intensity of the plasma spectra obtained by OES diagnostics at an applied voltage of 11 kV, frequency of 50 kHz, for argon gas flow rates of 0.5-2 L/min when used AC voltage. The spectral peaks appeared mainly in the wavelength range 200-1000 nm and were compared with the NIST database [19]. The highest peak in the diagnostic process of the argon gas spectrum was recorded at 810.99 nm, and some spectral peaks appeared for argon. Also, as a result of the gas flow rate increase, the emission process was evident due to the increase in the ionization process of gas atoms in the plasma column [18]. The spectrum shows five peaks for Si^{2+} at 312.74, 325.83, 356.06, 378.61, and 379.7 nm, comparing it with the NIST database. An increase in peak height appears when the flow rate exceeds 0.5 L/min.

The spectral emission results of silicon under the effect of DC voltage show much higher spectral emission intensities compared to the spectral intensities under effect the of AC voltage for the same gas flow rate variations. This is due to the main difference between DC and AC voltages, which is the direction of electric charge flow. In case of DC, the electric charge flows in one direction, from the positive terminal to the negative terminal of the power source. In case of AC, the direction of the electric charge reverses periodically, thus oscillating back and forth between the positive and negative terminals of the power source. The behavior of silicon was much more affected by DC voltage than AC voltage at constant applied voltage for both types of current.

From Eq. (1), the electron temperature (T_e) was calculated after representing the data obtained from the spectroscopic diagnosis and the highest recorded peaks with a graph in which $\mathrm{Ln}[\lambda_{ji}I_{ji}/hcA_{ji}g_i]$ is a function of E_j. From the resulting linear slope, as in figures (3) and (4), the temperature of the electron (T_e) of plasma was calculated using DC and AC voltages.

The electron density (n_e) was calculated from Eq. (2). Using DC voltage, the behavior of electron temperature and electron density agreed as shown in Fig. (4). The electron temperature (T_e) was increased from 2.22 to 2.67 eV and n_e was increased from 3.238×10^{16} to 33.05×10^{16} cm^{-3} in the generated plasma as a result of the increased gas flow rate in the system, as recorded in table (1), and this is consistent with the research [20]. When Using AC voltage, the behavior of electron temperature and electron density were in agreement as shown in Fig. (5). The T_e increased from 1.018 to 1.093 eV and n_e increased from 5.026×10^{16} to 6.897×10^{16} cm^{-3} in the generated plasma as a result of the increased gas flow rate in the system, and this is consistent with the reference [21].

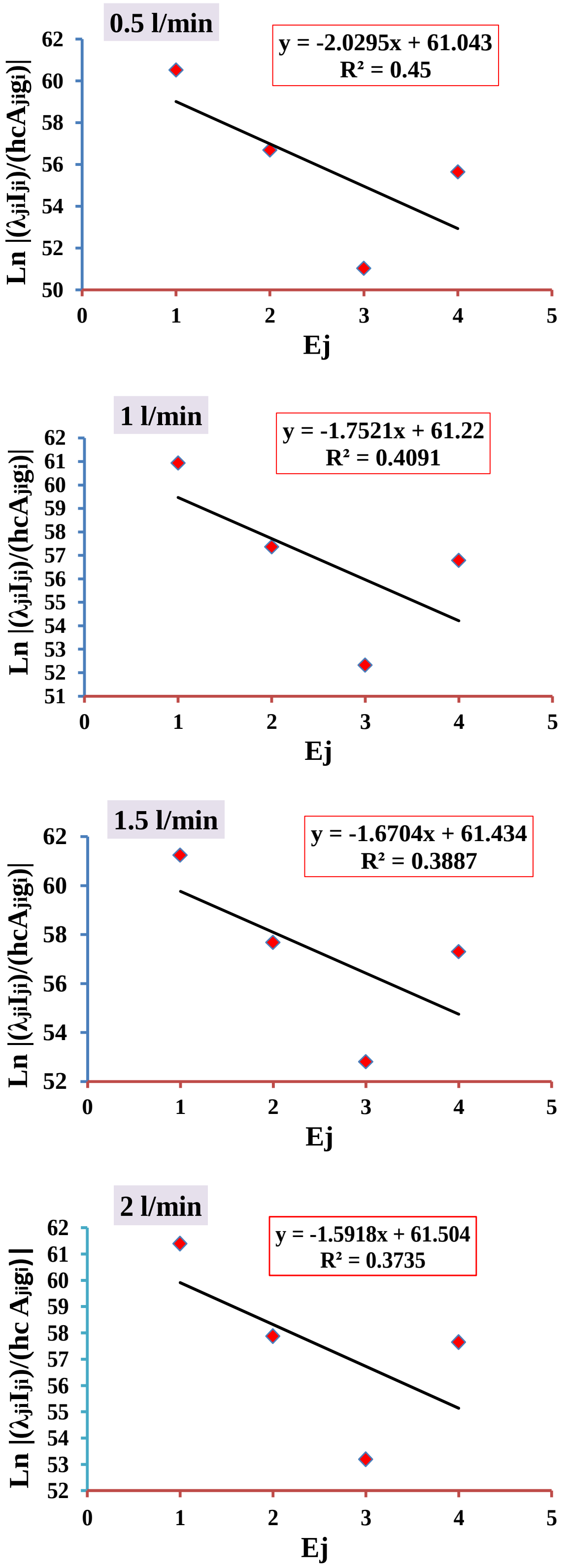

Fig. (3) Boltzmann plots of silicon plasma jet for different Ar gas flow rates 0.5-2 L/min using DC high voltage

Table (1) Plasma parameters of silicon plasma jet using DC high voltage at 11 kV and Ar gas flow rate of 0.5-2 L/min

Flow rate (L/min)	T_e (eV)	FWHM (deg)	n_e x10^{16} (cm^{-3})
0.5	2.22	18.46	3.238
1	2.44	18.56	3.256
1.5	2.57	18.71	3.282
2	2.67	18.84	3.305

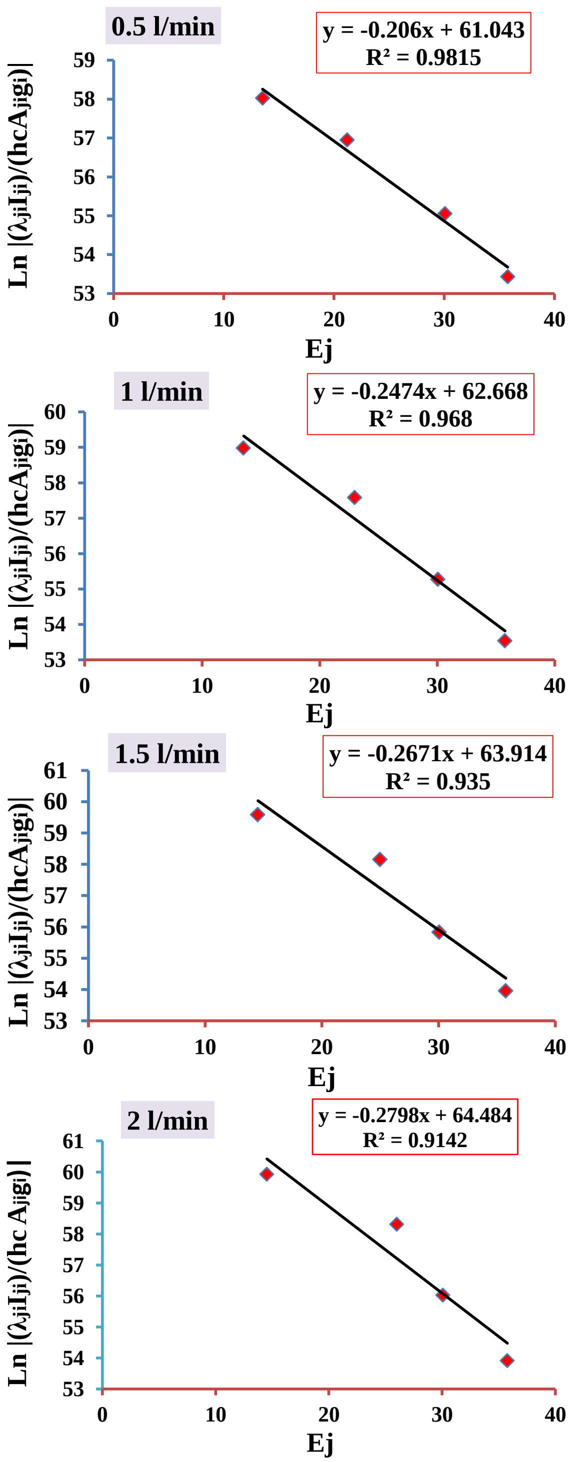

Fig. (4) Boltzmann plots of silicon plasma jet for different Ar gas flow rates 0.5-2 L/min using AC high voltage

Table (2) Plasma parameters of silicon plasma jet using AC high voltage at 11 kV and Ar gas flow rate of 0.5-2 L/min

Flow rate (L/min)	T_e (eV)	FWHM (deg)	n_e x10^{16} (cm^{-3})
0.5	1.018	10.97	5.026
1	1.033	13.44	6.280
1.5	1.069	14.54	6.694
2	1.093	14.76	6.897

The scaling gradients of figures (5) and (6) indicate a clear effect of the current type (DC and AC) as mentioned above, while the figure referred to also clarified the impact of changing the flow rate of argon gas and changing the current on the temperature and density of electrons, as it seems to be directly related to increasing the ionization state in the plasma column. With increasing flow, the state of the interaction of gas atoms between the two poles increases as a result of their acceleration from the cathode to the anode, which causes the disintegration of some bonds and the association of others between electrons and neutral particles, so secondary reactions occur that lead to collapse and thus increase the temperature and density of electrons as well.

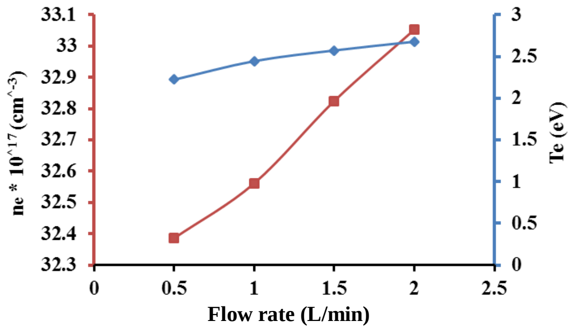

Fig. (5) Behavior of T_e and n_e of a silicon plasma jet in relation to argon flow rate using DC high voltage

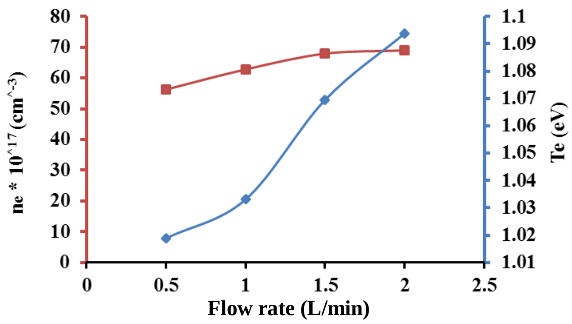

Fig. (6) Behavior of T_e and n_e of a silicon plasma jet in relation to argon flow rate using AC high voltage

4. Conclusion

The spectral lines resulting from the emission of silicon plasma in the plasma jet show the effect of direct external changes such as changing the type of current and the flow rate of argon gas. The study found that the type of current used affected the intensity of the spectral emission, indicating an increase in the temperature and density of the electrons and thus an increase in the number of collisions between molecules and excitation and ionization processes with the increase in the gas flow rate, of course. The spectral peaks produced using DC voltage were higher than the spectral peaks produced using AC voltage. The temperature and electron density recorded an increase from 2.22 to 2.67 eV, and from 3.238×10^{16} to 3.305×10^{16} cm^{-3}, respectively, with increasing gas flow rate when DC voltage was used, while the temperature and electron density increased from 1.018 to 1.093 eV, and from 5.026×10^{16} to 6.897×10^{16} cm^{-3}, respectively, with increasing gas flow rate when AC voltage was used. Therefore, it is clear that silicon metal shows different behavior with changing the current type and the DC current was the most influential on plasma produced in the plasma jet.

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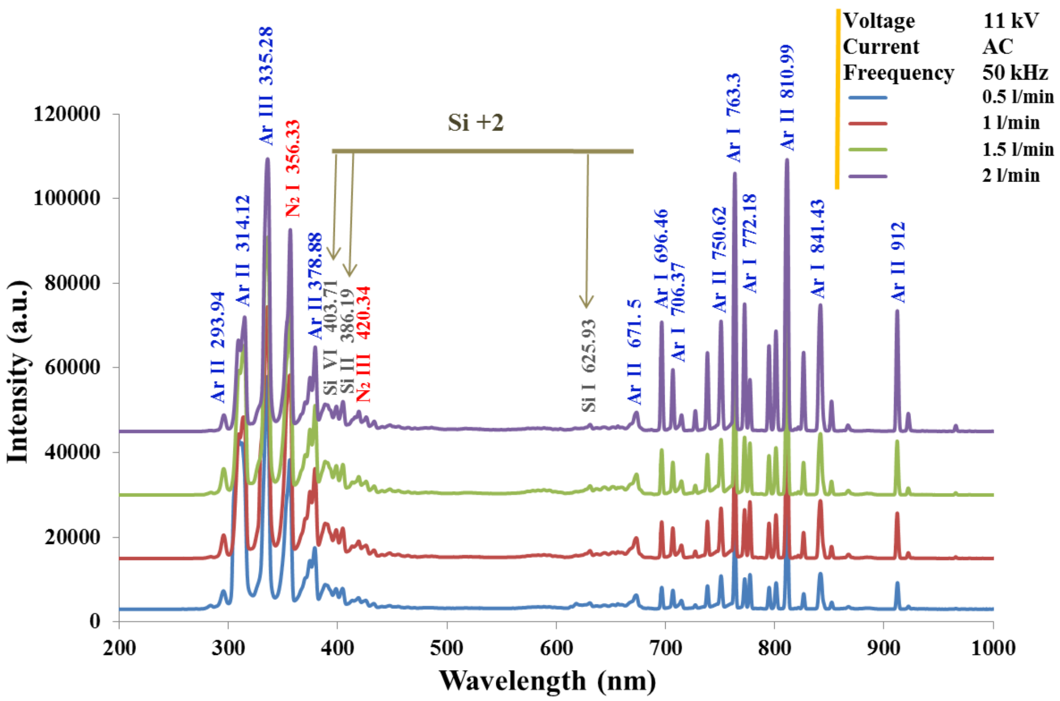

Fig. (1) Optical emission diagnostic spectrum of a silicon plasma jet system at various flow rates of Ar as using DC high voltage

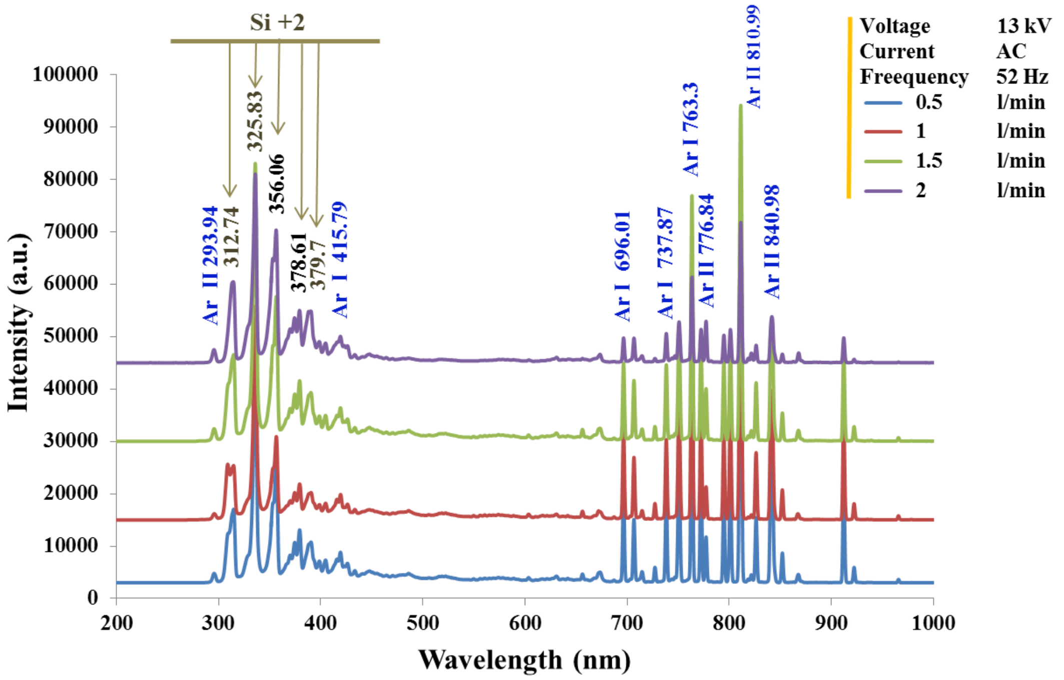

Fig. (2) Optical emission diagnostic spectrum of a silicon plasma jet system at various flow rates of Ar gas using AC high voltage

