The Study of the Characteristics of a Microwave Plasma Jet Operated with Ar at Atmospheric pressure

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ABSTRACT

In recent years, non-thermal atmospheric pressure plasma has attracted wide interest in industrial and biomedical fields due to its many advantages, such as its high efficiency, simple systems, easy operation, non-toxic residue, and low cost. In this project, non-thermal (cold) plasma generated using a voltage source with a precise frequency (microwave up to 2.4GHz) using argon gas. The electrical properties studied to describe the discharges of argon gas plasma jets at different flow rates (Flow= (1, 2, 3, 4) L/min) and with voltages (150 V). The produced plasma jet column will be analyzed using Optical Emission Spectrometry (OES) technology to determine plasma parameters such as electron temperature (T_e), electron density (n_e), plasma frequency (f_p), Debye length (λ_D), and Debye (N_D) number of the argon plasma jet. We use the Boltzmann plot to determine the electron temperature (T_e) in the plasma, and the electron density (n_e) is calculated by Stark broadening. The value of the electron temperature decreases from (0.991-1.273) eV and the electron density rises from (2.173-3.664) $\times 10^{17}$ cm^{-3} with higher gas flow rates, also the Plasma plume length rises from (1.1-3.5) cm with higher gas flow rates, while the plasma jet temperature decreased with higher gas flow rates.

Introduction

A non-thermal (or cold or low temperature) plasma is a partially ionized gas with electron temperatures much higher than ion temperatures.

A microwave discharge (MD) is an electrical discharge caused by electromagnetic waves with frequencies greater than 300MHz. The wavelengths used by microwaves range from millimeters to tens of centimeters and must match microwave frequencies accepted in industrial, medical, and scientific applications. The most commonly used frequency is 2.45GHz. [1]

A microwave plasma system is mainly composed of three main parts (1) a microwave generator (magnetron), (2) a waveguide, and (3) a plasma chamber. Besides these three main parts, there are other parts such as the vacuum unit, pressure gauges, and gas supply.

One of the most common methods for diagnosing plasma is optical emission spectroscopy. Diagnostic methods for plasma spectroscopy are based on the measurement of emission or absorption intensities, continuum and half-width lines, and line shifts. The emission of light from plasma occurs mainly through the influence of electrons to excite atoms or molecules in an excited state, then it relaxes to a lower energy state, releasing photons containing energy equal to the difference between the two energy states. Analysis of photon energy (wavelength of light) and spectral emission information of the species can be used to infer the composition of the species it produces [2].

Optical Emission Spectroscopy is part of the electromagnetic light spectrum and part of the ultraviolet spectrum (130-800) nm[3].

In this method, the radiation emitted by the plasma beam is analyzed to calculate the parameters of the plasma. Optical emission spectroscopy is used to obtain facts about the plasma properties such as electron temperature, plasma density, and type. The main purpose of this study is by using optical emission spectroscopy to study plasma parameters using spectral lines emitted from Argon atoms

surrounding the plasma. To calculate (Te) we use the Boltzmann distribution as the following equation [4].

$$Ln\left(\frac{I_{ji}\lambda_{ji}}{A_{ji}\,g_j}\right) = -\frac{E_j}{K_B\,T} + C \ldots\ldots\ldots 1$$

Where:-

Iji: is the intensity of the emitted line.

λji: its wavelength.

gi: is statistical weight the statistical weight of the upper level which can be calculated from the total angular momentum quantum number J by g = 2J + 1.

Aji: is the transition probability.

Ei: is the excitation energy (in electron volts)

k_B: is the Boltzmann constant.

The curve between different energy verse values of $Ln\left(\frac{I_{ji}\lambda_{ji}}{A_{ji}\,g_j}\right)$ verses the energies of the higher degree of the E_i, giving a straight line with a slope (-1/T_e). The electron temperature (T_e) is associated with the slope of the linear fitting [5].

We can use the stark broadening of two different emission lines to determine the density of the electron From a technical factor of view, this method is extra affordable than different methods. It can offer facts approximately the electron density with high accuracy. The decision is specifically due to the broadening of the spectral lines emitted by the plasma and the interaction of the radioactive atoms with the surrounding charged particles. To calculate the electron density (in cm^{-3}) using the equation:

$$n_e = \frac{\Delta\lambda\,FWHM}{2(w)}x(\,N_r)\ldots\ldots\ldots\ldots\ldots 2$$

n_e: is the electron number density in cm^{-3}

$\Delta\lambda\,FWHM$, is the full width at half maximum (FWHM) of the line.

w: is the electron impact parameter (stark broadening value) [6-7] .

N_r: is the reference electron number density which equals 10^{16} cm^{-3} for neutral atoms and 10^{17}cm^{-3} for singly charged ions [8].

The electron Debye length is defined as a microscopic maximum spatial scale for the charge-separation [9]:

$$\lambda_{D=}\sqrt{\frac{\epsilon_\circ\,K_B\,T_e}{n_e\,e^2}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Where, λ_D: the electron Debye length.

$\epsilon_\circ$: Vacuum permittivity.

e^2: Electronic charge.

We can also find the number of particles (N_D) in a sphere that has a radius equal to λ_D (Debye length) [10], using the equation:

$$N_D = \frac{4\pi}{3}n_e\lambda_D{}^3 n_e = 1380\,T^{3/2}\,/\,n_e{}^{1/2}\,(T\,in\,K)\,\ldots\ldots 4$$
[11]

A practical formula for the plasma frequency (f_{pe}) is [12]:

$$f_{pe} = \frac{w_{pe}}{2\pi} \approx 9\sqrt{n_e}\ldots\ldots 5$$

ω_{pe}: is the plasma frequency of the electron.

Experimental setup

The experimental setup can be explained in Fig. 1. The microwave induced plasma jet (MIPJ) system is installed in our laboratory using simple, low-cost materials con get it in the local market. The main components of the (MIPJ) system are:

1- Microwave source (magnetron).

2- Rectangular guide.

3- Tube of Plasma discharge.

4- The ignition of the system.

5- Gas supply and flow meter.
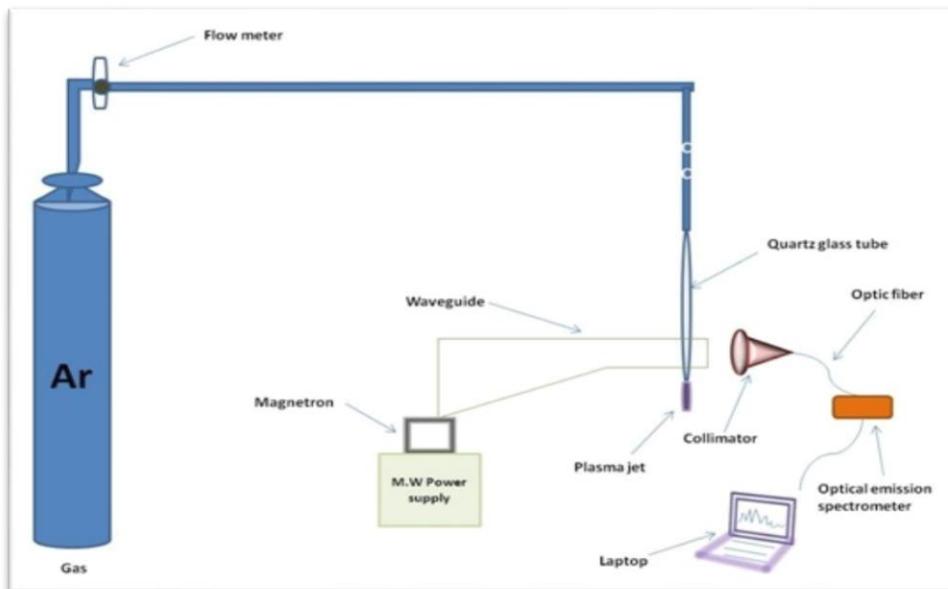
Fig. 1: Diagrammatic drawing of the MIPJ system

We build a microwave plasma system (a bottle of ionized gas, which is usually an inert gas, and we use Ar gas in this work. The gas passage is controlled by a flow meter unit liter/min and is fixed with the connecting tube between the plasma needle and the gas bottle.

To generate microwave radiation at a frequency of 2.4 GH, we use a magnetron connected to a high voltage circuit that converts the voltage applied to it into microwave rays, and these rays pass through a part called a waveguide, which collects these rays and directs them to a Quartz glass tube. The (OES) is placed in front of the plasma torch, where the lens collects the light and drops it into the middle of the optical fiber (Fiber optic) made of very pure special glass, the light beam is transmitted to a light analyzer that analyzes the light into its wavelengths with measuring the intensity shown on the calculator screen.

We study the properties of plasma by changing the gas flow rate and inlet discharge voltage. For each case, we study the plasma spectrum by (OES) and the plasma parameters such as measuring the plasma plume length which represents the length of the distance between the plasma nozzle and the end of the jet, it changes for each case and is measured by an ordinary measuring ruler. We also measure the temperature of the electrons T_e (Boltizman's equation) and their density n_e (Starck Product equation). We also measure the temperature of the plasma column T_{Body} by a digital thermometer.

Results and discussion

Figure (2) represents the optical emission spectroscopy (OES) for microwave plasma jet in Ar gas with 150 volts at different gas flow rates (1,2,3 and 4) L/min. Most of the ArI peaks are located in the range (696.54 - 866.7944)nm[13]. We can look at the peak intensities increase with increasing gas flow rates as a result of an increasing number of atoms density which leads to an increasing number of excited atoms. The NIST database is used to obtain information and constants for each wavelength of line intensity in the argon plasma jet [14].
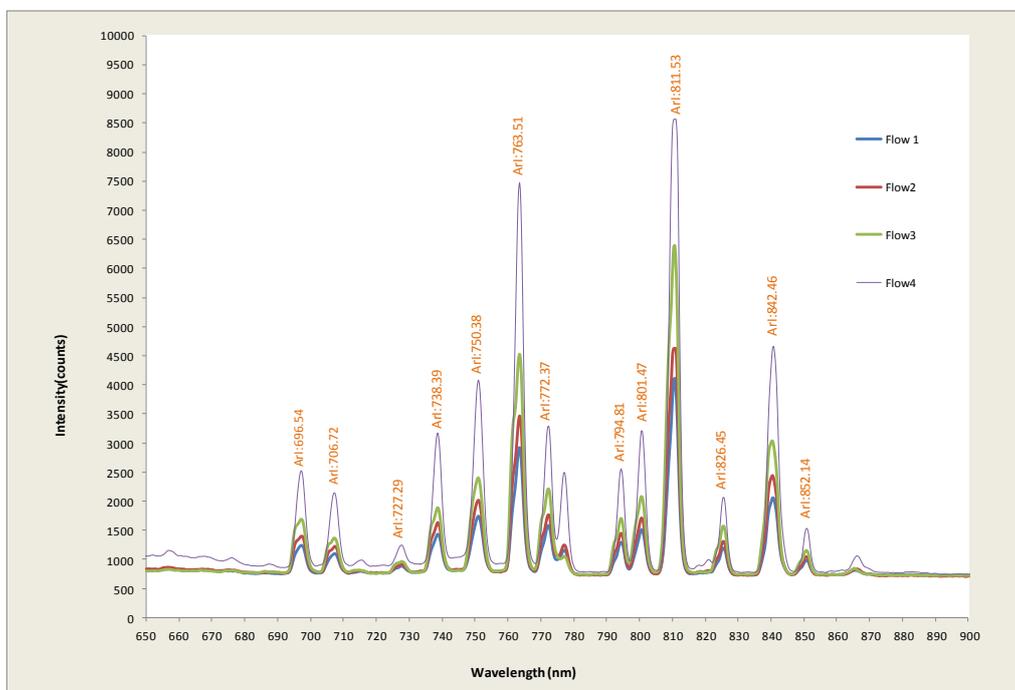
Fig. 2: Emission spectra for Microwave plasma jet in Ar with different gas flow rates.

The Boltzmann plot method uses to determine electron temperature (T_e). In this method three lines have been chosen (696.54, 801.47, and 811.53) nm, all of these lines characterized by having the same lower energy level E_i with different upper energy levels E_k. [15]. Table (1) contains argon lines considered with their spectroscopic data, those values of the parameters have been taken from NIST [14].

Table 1: ArI lines with spectroscopic data used in the Boltzmann plot method[14].

Species	Wavelength (nm)	$A_k \times 10^6$(1/s)	E_i (eV)	E_k (eV)	g_k
ArI	696.54	6.39	11.54	13.32	3
ArI	801.47	9.28	11.54	13.09	5
ArI	811.53	33.1	11.54	13.07	7

After substitute values, A_k, E_k, g_k, I, and λ in equation (1), $Ln\left(\frac{I_{ji}\lambda_{ji}}{A_{ji} g_j}\right)$ Can be plotted as a function of E_k as in figure (2), it consists of the statistical coefficient (R^2) and equations of fitting lines. R^2 indicates the priority of the linear fit. We can note that the value of R^2 ranges from (0.953 to 0.976) eV. T_e linked to the inverse slope of the linear fitting.
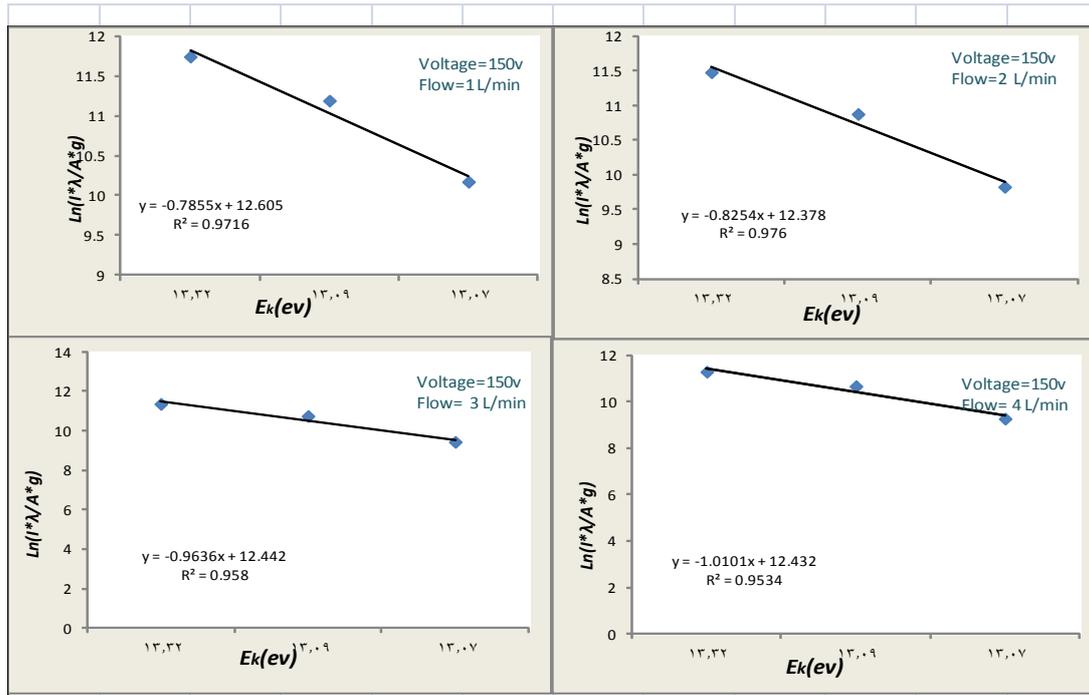
Fig. 2: Boltzmann plot from ArI lines produced by Microwave plasma jet with different gas flow rates.

Fig. 3: shows the 696.54 nm ArI line peak profile. By using Lorentzian fitting and finding the full width at half maximum (FWHM) to determine electron density with change gas flow rates using stark broadening of ArI (696.54nm) line is collected through the following relation [16]:

$$Ln \, n_e = 44.2476 + 1.20 \, Ln \, \Delta\lambda_{\frac{1}{2}} - 0.6 \, Ln \, T_e$$

Then,

$$n_e = \exp\left(44.2476 + 1.20 \, Ln \, \Delta\lambda_{\frac{1}{2}} - 0.6 \, Ln \, T_e\right)$$

Where T_e in Kelvin and $\lambda_{1/2}$ is the line width at half maximum intensity.
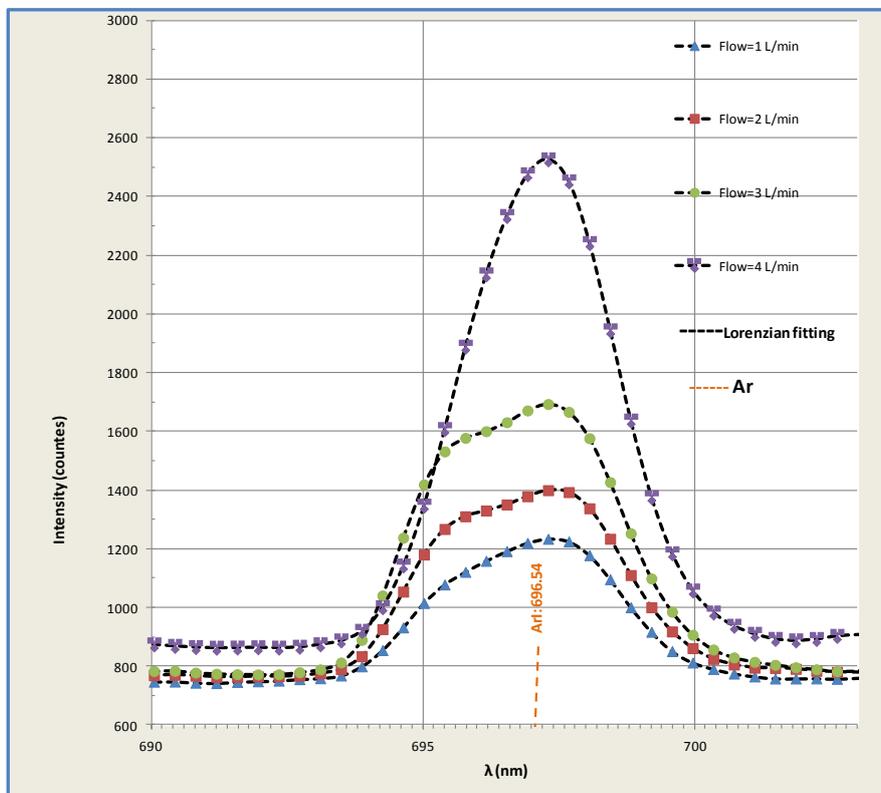
Fig. 3: ArI 696.54 nm peaks broadening and their Lorentzian fitting at differing flow rates.

Figure (4) show the relation between the (T_e) and (n_e) with gas flow rate. (n_e) rises slightly from (2.173×10^{17} – 3.664×10^{17}) cm^{-3} with increasing gas flow rates from (1-4) L/min produced because of increasing ionization electron–neutral collisions with rises of atoms density, which produces more electrons. This increase causes a decrease in the rate of mean values of electron temperature as a result of losses of electron energies by excitation and ionization collision [17].
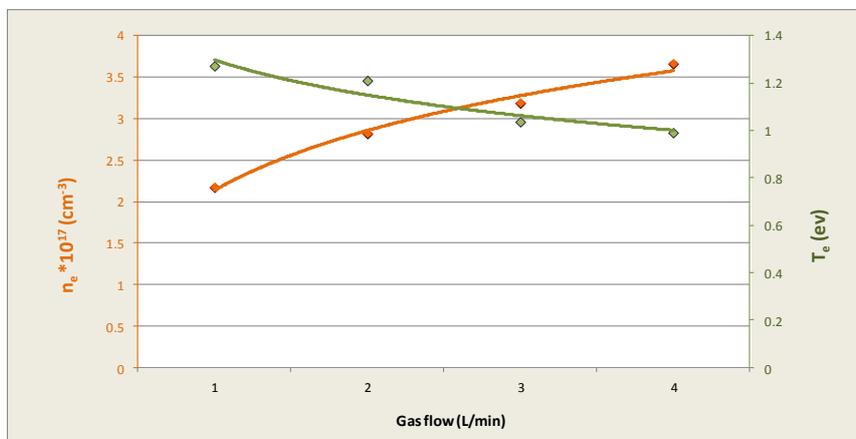
Fig. 4: The variation of (n_e) and (T_e) for microwave plasma jet in Ar with different gas flow rates.

Table.2: shows the calculated values of Debye length (λD), plasma frequency (f_p), and Debye number (Nd) for microwave plasma jets in Ar with different gas flow rates.

Table 2: Parameters of a microwave plasma jet in Ar with different gas flow rates.

Flow (L/min)	T_e (eV)	FWHM (nm)	n_e*10^{17} (cm^{-3})	$f_p *10^{10}$ (HZ)	$\lambda_D *10^{-5}$ (cm)	N_d
1	1.273	3.3	2.173	0.419	1.798	5.311
2	1.211	4	2.821	0.478	1.539	4.325
3	1.037	4.1	3.189	0.508	1.339	3.223
4	0.991	4.5	3.664	0.544	1.221	2.809

Plasma plume length:

To study the plasma torch length, we depend on the gas flow rate for Ar which generates different plumes length of plasma. To figure (5), the maximum length of the Ar plasma plume reaches 3.5(cm) at 4 L/min, which means the higher gas flow rate gives a longer plasma plume.

Table 3: The relation between the plasma plume length in different Ar gas flow rates.

Ar	
Flow (L/min)	Plasma plume length(cm)
1	1.1
2	1.9
3	3.3
4	3.5
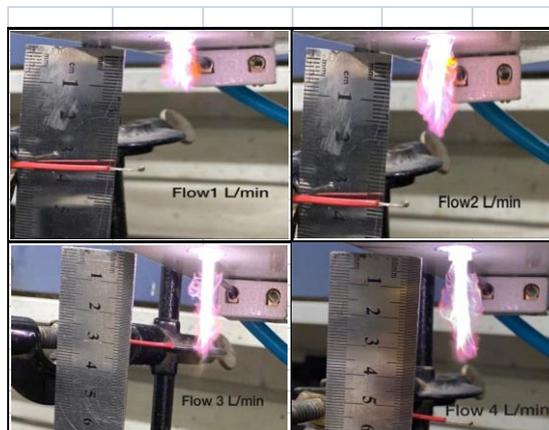
Fig. 5: Photographs of plasma plumes for Ar of different gas flow rates at voltage 150(V).

Plasma jet temperature:

The plasma jet temperature was measured with different Ar gas flow rates (different plume lengths) and different times by using a thermocouple. During all the measurements the room temperature was 23∘C. Figure (6) show the plasma temperature as the function of the time for different gas flow rates, the highest temperature in argon plasma jet reached 180º C at two minutes with a gas flow rate of 1 L/min, while the lowest temperature reached 37ºC at two minutes with a gas flow rate of 18 L/min. This indicates that the plasma jet temperature rise with increasing time and decreased with a higher flow rate. That improves the fact that increasing the gas flow rate cools the plasma [18].
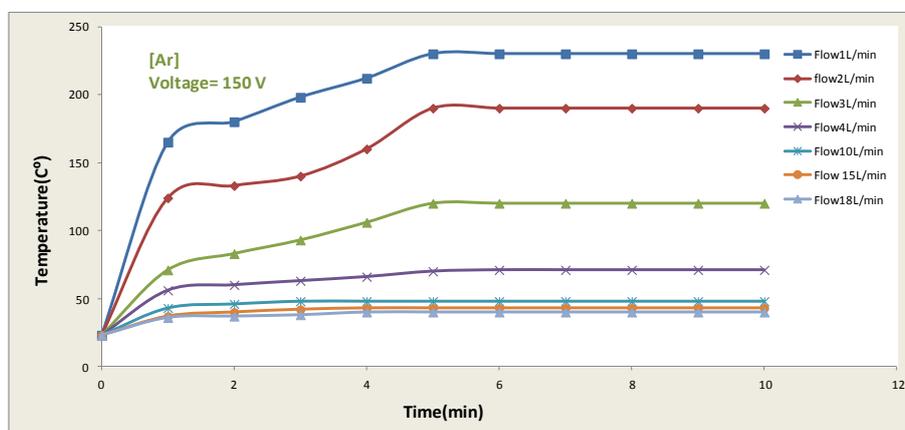
Fig. 6: Shows Ar plasma jet as a function of the time for different gas flow rates.

Conclusions

Microwave operated with Ar at atmospheric pressure has been used to provide Plasma jet. The spectrum lines emitted from the plasma jet depend on the operational situation. And located that the emission intensity raises with the rises in the gas flow rate. The electron temperature decreases and electron density rise with raising the gas flow rate. We find that it's miles feasible for the system to successfully generate suitable plasma temperatures, which can be used in a variety of applications.

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دراسة الخصائص والتحليل الطيفي لنافث البلازما الذي يعمل بالموجات الدقيقة وعند الضغط الجوي وباستخدام غاز الاركون

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الملخص

في السنوات الأخيرة ، اجتذبت بلازما الضغط الجوي غير الحراري اهتمامًا واسعًا في المجالات الصناعية والطبية الحيوية نظرًا لمزاياها العديدة ، مثل كفاءتها العالية وأنظمتها البسيطة والتشغيل السهل والمخلفات غير السامة والتكلفة المنخفضة. في هذا المشروع ، تم إنشاء بلازما غير حرارية (باردة) باستخدام مصدر جهد بتردد دقيق (ميكروويف يصل إلى 2.4 جيجا هرتز) باستخدام غاز الأرجون. تم دراسة الخواص الكهربائية لوصف تفريغات نافثات بلازما غاز الأركون و بمعدلات تدفق مختلفة (Flow=(1,2,3,4 (L/min) وبفولتية (150 V). سيتم تحليل عمود البلازما المنتجة بتقنية مطياف الانبعاث البصري (OES) لتحديد معلمات البلازما مثل درجة حرارة الإلكترون (T_e) وكثافة الإلكترون (n_e) وتردد البلازما (f_p) وطول ديباي (λ_D) ورقم ديباي (N_D) لنافث بلازما الارجون. تم استخدام مخطط Boltzmann لحساب درجة حرارة الإلكترون في البلازما (T_e) ، وتم حساب كثافة الإلكترون (n_e) عن طريق توسيع Stark. تقل قيمة درجة حرارة الإلكترون eV(1.273-0.991) وترتفع كثافة الالكترون ($2.173-3.664)x10^{17}cm^{-3}$) مع معدلات تدفق غاز أعلى ، كما يرتفع طول عمود البلازما من cm(3.5-1.1) مع تدفق غاز أعلى في حين انخفضت درجة حرارة البلازما النفاثة مع ارتفاع معدلات تدفق الغاز .