The Effect of Gas Flow on Plasma Parameters Induced by Microwave

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Abstract:

In this paper, construction microwaves induced plasma jet(MIPJ) system. This system was used to produce a non-thermal plasma jet at atmospheric pressure, at standard frequency of 2.45 GHz and microwave power of 800 W. The working gas Argon (Ar) was supplied to flow through the torch with adjustable flow rate by using flow meter, to diagnose microwave plasma optical emission spectroscopy(OES) was used to measure the important plasma parameters such as electron temperature (Te), residence time (R_t), plasma frequency (ω_{pe}), collisional skin depth (δ), plasma conductivity (σ_{dc}), Debye length(λ_D). Also, the density of the plasma electron is calculated with the use of Stark broadened profiles.

Key words: Boltzmann plot, Plasma parameters, Microwave plasma jet, Plasma diagnostics.

Introduction:

Plasma is commonly an ionized gas. It is combining of charge particles (electron, ion and molecules). The term ionized return to the existence of one or more free electron. That are not required to an atom or molecules (1,2). It has free charge particles where the positive and negative charges approximately stasis each other at the level of the macroscopic. It resulted when the elements are heated to temperature more than the thermal energies and above binding energies for special state of matter. When the environment temperature increases the division of atoms can break down to negative charge electron and positive charge ion. These particles will contact with each other through the e.m. radiation(3). A microwave plasma is a type of plasma that has a high frequency electromagnetic radiation in the GHz range. Microwave generated plasma devices are preferred over other types of plasma sources because they are electrodeless plasma, so the mission of replacing or cleaning the electrodes and filaments is avoided. More importantly, the plasma is free from impurities that can come from the sputtering or evaporation of these parts during operation. This plasma can be excited in special geometries, and it can provide stable, continuous plasmas over a large range of gas pressures (4,5).

This paper presents the experimental work including the design and construction of a microwave plasma system, its operation at atmospheric pressure at standard frequency of 2.45 GHz and microwave power not exceeding 800 W. The atmospheric-pressure microwave plasma parameters were determined by optical emission spectroscopy (OES) method. The Boltzmann plot method was used to calculate excitation temperature of argon, and the electron density was calculated by local thermal equilibrium assumption (6, 7,8).

Materials and Methods:

Electron Temperature:

In this work, Electron temperature (Te) was determined using Boltzmann plot method. In this method, several spectral lines are considered (represent ArI); all of these lines have a similar lower energy level E_i with different upper energy levels E_k. Five lines have been chosen (696.54, 763.51, 772.37, 801.47 and 811.53) nm (9). Table 1 lists argon lines considered with their spectroscopic data; these values of the parameters have been taken from NIST(10).

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Table 1. Spectroscopic data of ArI lines used in Boltzmann plot method(7).

Species	Wavelength (nm)	$A_k \times 10^6$ (s^{-1})	E_i (eV)	E_k (eV)	g_k
ArI	696.54	6.39	11.54	13.32	3
ArI	763.51	24.5	11.54	13.17	5
ArI	772.37	5.18	11.54	13.15	3
ArI	801.47	9.28	11.54	13.09	5
ArI	811.53	33.1	11.54	13.07	7

To determine the electron temperature by using the following equation: (2)

$$Ln\left(\frac{I_{ji}\lambda_{ji}}{A_{ji}\,g_j}\right) = -\frac{E_j}{kT} + C \quad (2)$$

where C is a constant and substitute values of A_k, E_k and g_k from Table (1) . Now, by plotting the term $Ln\left(\frac{I_{ji}\lambda_{ji}}{A_{ji}\,g_j}\right)$ in the vertical axis with E_j in the horizontal axis from equation (1) for several lines (all of these lines have the same lower energy level), the electron temperature T_e, which is related to the slope of the linear fitting (11,12,13) .

Electron Density

The electron density (n_e) was calculated using the following equation

$$n_e = \exp\left(44.2476 + 1.20\,Ln\,\Delta\lambda_{\frac{1}{2}} - 0.6\,Ln\,T_e\right) \quad (3)$$

The Stark broadening (full width at half-maximum, FWHM) $\Delta\lambda_{1/2}$ of the spectral line ArI (696.54nm) line was measured from emission spectra and substituted in equation (3) with the values of T_e (that obtained from equation (2))(14).

Electron Residence Time

Equation (4) clarifies the time of particles existence in the plasma(15):

$$R_t = \frac{L_j A}{u} \quad (4)$$

The electron residence time (R_t) was calculated after substituting the value of plasma flame length L_j with different gas flow rates.

Plasma Frequency

These oscillations occur at a frequency called the plasma frequency of electron (ω_{pe}) which can be written as (16):

$$\omega_{pe} = \sqrt{\frac{e^2\,n_e}{\varepsilon_\circ\,m_e}} \quad (5)$$

The plasma frequency ω_p was calculated after substituted the n_e from equation (3) . The results show that ω_p was on the order 10^{13} H_Z which exceeds the microwave frequency 2.45×10^9 H_Z that is used to create our plasma in four orders.

The Collisional Skin Depth

Collisional skin depth (δ) of plasma was calculated from the following equation:

$$\delta = \frac{c}{\omega_p}\sqrt{\frac{2\nu_m}{\omega}} \quad (6)$$

where c is the speed of light in a vacuum, ω_p is the frequency of plasma, ν_m is the frequency of momentum collision, and ω is the frequency of microwave.

whereas this equation valid ω_{pe}, $\nu_m \gg \omega$ and that verified by estimated momentum collision frequency ν_m from equations

$$\nu_m = \nu\,\frac{m_1+m_2}{2m_1} \quad (7)$$

which were given values in order 10^{15} H_Z.

Plasma Conductivity

Equation (8) clarifies the plasma conductivity, σ_{dc}, is given by

$$\sigma_{dc} = \frac{2}{\omega\mu_o\delta^2} \quad (8)$$

where ω is the frequency of microwave, μ_o is the constant of vacuum permeability , and δ is the collisional skin depth.

Debye length

The applied electrical potential will therefore develop mostly near the surfaces, over a distance λ_D, called the Debye length as defined by(17,18).

$$\lambda_D = \left(\frac{\varepsilon_o k_B T_e}{n_e e^2}\right)^{1/2} \quad (9)$$

where n_e is the density of the electrons $\left(m^{-3}\right)$, ε_O is Permittivity of free space

Experimental setup:

The diagram of the setup used for experimental investigations of microwave plasma sources is shown in Fig. 1. Its essential components are: Microwave generator (magnetron), Tapered rectangular waveguide, Plasma discharge tube, Ignition system, Gas supply and flow controller.
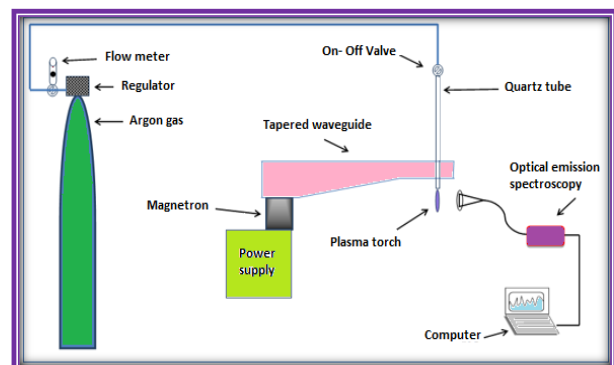

Figure 1. A schematic diagram of the microwaves induced plasma jet system.

The first step of this paper is applied a variable input AC voltage on the microwave source (magnetron) ranged from 150 to 220 volt. After operating the magnetron, argon as a working gas was inserted through a discharge quartz tube with diameter 10 mm at different flow rates (1 ,2 ,3,4 and 5) ℓ/min. Optical emission spectroscopic was used to measure a microscopic parameters of the plasma jet such as electron temperature and electron density.

Results and Discussions:

Figure 2 illustrates the Boltzmann plot for the equation 2 for single case. With the diagnostic method described above, electron temperatures measured as gas flow rate, discharge tube diameter 10 mm and applied voltage varied in the ranges (1-5) ℓmin^{-1},of 150-220Volt. As shown in Fig. 3 which shows the relation between electron

temperatures and applied voltage at a different gas flow rate. At the beginning of the operation, the gas flow rate was 1ℓ/min the electron temperature was 0.07778eV at 150 volts; this value remains the same before the microwave (0v). The electron temperature increases with voltage until it reaches 0.19232eV at 190v after 190v. The value decreases to 0.1601eV at 200v and remains constant for higher voltage. For all the other gas flow rates (2 to 5) ℓ/min, the electron temperature at 0v has the value of 0.04eV. At 2 ℓ/min the electron temperature starts at a value of 0.11723eV and reach its maximum value 0.21317eV at 170v. The electron temperature decreases at a voltage range from 170v to 190v and for higher voltage, the electron temperature remains approximately constant. For 3 ℓ/min curve the electron temperature at 150v was 0.1803eV and this value decreases to 0.14078eV at 160v. The electron temperature remains constant at a voltage higher than 160v. At 4 ℓ/min curve the value of electron temperature was constant for all applied voltages with the value of 0.14072eV except at 160v where the electron temperature was 0.10646eV. The 5 ℓ/min curve shows the least electron temperature at any voltage. The electron temperature was 0.02633eV at 150v and increases to 0.10646eV at 160v. At a higher voltage, the electron temperature varied between 0.1 and 0.15 eV.

Figure 4 demonstrates the electron density as a function of applied voltage at a different gas flow rate. Before the microwave at (0v) the electron density for 1 ℓ/min gas flow rate was 9.22E+16 cm$^-$^{3}, but for the gas flow rate range from 2 to 5 ℓ/min the average electron density was 1.3E+17 cm^{-3}.The maximum value of electron density was 3.16482+E17 cm^{-3} for 3 ℓ/min at 180 volts flowed by 2.91345E+17 cm^{-3} at 200v. The minimum value for 3 ℓ/min at range from 150v to 160v was less than 1E+17.For 4 ℓ/min gas flow the major value lies between 170v to 210v at electron density range from 2E+17 cm^{-3} to 3E+17 cm^{-3} . The maximum value for electron density at 1 ℓ/min gas flow was 2.18179E+17 cm^{-3} at 170v, the rest of the values were less than 1.5E+17 cm^{-3}. The bar chart for 5 ℓ/min at 150v shows the electron density was 1.76974E+17 cm^{-3} which represents the maximum value. At voltage range from 160v to 220v, the electron density was less than 1E+17 cm^{-3}. At 2 ℓ/min all the values of electron density were less than 1E+17 cm^{-3} for all applied voltages.

The change of electron residence time has been studied as a function of the applied voltage from 0 to 220 volts, where 0v means without a microwave. The different gas flow rates have been used as shown in Fig. 5. As the voltage increases, the electron residence time also increases, but when the gas flow rate increases the electron residence time decreases at any voltage.

The highest value of electron residence time is measured at 1 ℓ/min. At 0v the value was 188.4msec It increases rapidly with voltage until it reaches 438.03msec at 220v. For any applied voltage, the drop of electron resistance time from 1 ℓ/min to 2 ℓ/min is significantly large. The electron residence time curve for gas flow rate ranges from 3 to 5 ℓ/min which behave the same and their results are close to each other.

For 2 ℓ/min gas flow rate, the electron residence time was 122.46msec at 0v and the maximum was 223.725msec at 220v. For 3 ℓ/min gas flow rate, the electron residence time was 89.91msec at 0v and the maximum was 161.71msec at 220v. For 4 ℓ/min, the electron residence time was 88.315msec at 0v and the maximum was 131.88msec at 220v. Finally, at 5 ℓ/min, the value was 73.476msec at 0v and the maximum was 113msec at 220v.

In Fig. 6 the relation between the measured plasma frequency and the applied voltage at different gas flow rates is shown. The plasma frequency was measured at gas flow rates of (1, 2 , 3 , 4 and 5) ℓ/min. At 1 ℓ/min the plasma frequency was 1.71E+13Hz at 0v where no microwave was ignited. The frequency increases gradually with the increase of voltage until it reaches the maximum frequency value of 2.63E+13Hz at 170v. At voltage range from 180v to 220v an average frequency was calculated and its value was 1.43E+13Hz. For 2 ℓ/min the frequency at 0v was 2.03E+13Hz and at voltage range from 150v to 220v the average frequency was 1.53E+13Hz. For 3 ℓ/min the frequency was 2.03E+13Hz at 0v. The frequency decreases to its minimum of 1.47E+13Hz at 150v and remains constant at 160v then the frequency increases with voltage above 170v until it reaches its maximum value of 2.63E+13Hz at 180v. The behavior of 4 ℓ/min bar chart is similar to 3 ℓ/min where it starts with frequency of 2.03E+13Hz before the microwave then decreases to average minimum value of 1.5E+13Hz at both 150 and 160v. Above 170v the frequency increases with voltage until it reaches the maximum value of 3.05E+13Hz at 190v and the value drops slowly at higher voltage until it reaches 220v with frequency of 1.72E+13Hz. Finally the 5L/min has frequency of 2.06E+13Hz, reaching to its maximum at 150v where the frequency was 2.37E+13Hz. This value was the highest frequency measured at all gas flow rates. The frequency drops to average of 1.61E+13Hz at voltage range from 160v to 220v.

Fig. 7 shows the relationship between skin depth and applied voltage. The skin depth was calculated at different gas flow rates before and after the

microwave at voltage rang from 150v to 220v. The skin depth for 1 ℓ/min gas flow rate was 30.12788cm before microwave. After the microwave the average skin depth at voltage range from 150v to 170v was 25.43cm and the average skin depth for voltage range from 180v to 220v was 43.82cm.

At 2 ℓ/min the skin depth was 22.13cm at 0v where no microwave was ignited. The skin depth gradually increases with the increase of voltage until it reaches to the maximum value of 62.2cm at 170v. The rest of the values have less value than 44.9cm at applied voltage range from 180v to 220v. For 3 ℓ/min the skin depth starts at 22.25cm before the microwave and increases to 41.7cm at both 150 and 160 volt. The skin depth at voltage ranges from 170v to 220v was represented as average and the value was 21.95cm. For 4 ℓ/min the skin depth start at 21.99cm before the microwave and increases to 41.7cm at both 150 and 160 volt. The skin depth at voltage range from 170v to 220v was represented as average and the value was 21.95cm. Finally, the skin depth for 5 ℓ/min gas flow rate before the microwave was 21.47cm and the value increases to average of 35.6cm at voltage range from 160v to 220v. The plasma conductivity was measured before and after the microwave at different gas flow rates and the data were represented as shown in Fig. 8 between the plasma conductivity and the applied voltage. When the gas flow rate is 1 ℓ/min, the plasma before the microwave (0v) has a value of $0.71(\Omega m)^{-1}$. This value increased with the increase of applied voltage until it reached the maximum value of $1.26(\Omega m)^{-1}$ and the value dropped to an average conductivity of $0.348(\Omega m)^{-1}$ at voltage range from 180v to 220v. At 2 ℓ/min gas flow rate, the maximum value $1.33(\Omega m)^{-1}$ was indicated before the microwave. This value decreases with the increase of voltage until it reaches $0.17(\Omega m)^{-1}$ at 170v, where this value is the minimum value. The conductivity increases again to average value of $0.428(\Omega m)^{-1}$ at voltage range from 180v to 220v. For 3 ℓ/min the conductivity was $1.34(\Omega m)^{-1}$ at 0v the conductivity decreases to its minimum of $0.37(\Omega m)^{-1}$ at 150v and remains constant at 160v then the conductivity increases with voltage above 170v until it reaches its maximum value of $1.83(\Omega m)^{-1}$ at 180v. The behavior of 4 ℓ/min bar chart is similar to 3 ℓ/min where it starts with conductivity of $1.34(\Omega m)^{-1}$ before the microwave then decreases to average minimum value of $0.45(\Omega m)^{-1}$ at both 150 and 160v. Above 170v the conductivity increases with voltage until it reaches the max value of $1.69(\Omega m)^{-1}$ at 190v and the value drops slowly at higher voltage until it reaches 220v with conductivity of 1. Finally, the 5 ℓ/min has conductivity of $1.41(\Omega m)^{-1}$ that reaches its

maximum at 150v, where the conductivity was $2.37(\Omega m)^{-1}$. This value was the highest conductivity measured at all gas flow rates. The conductivity drops quickly to average of $0.52(\Omega m)^{-1}$ at voltage range from 160v to 220v.

Debye length was demonstrated as a function of the applied voltage as shown in Fig. 9. The data were represented as bar chart at a different gas flow rate. At 0V, it indicates that no microwave has been applied. The Debye length at gas flow rate range from 2 to 5 ℓ/min has an average value of 4E-6cm. At 1 ℓ/min gas flow rate the value was 6.85E-6cm. This value was higher than average Debye length of all other gas flow rates. When the microwave is applied to 1 ℓ/min gas flow the Debye length starts with 5.96425E-06cm at 150v; this value remains nearly the same for 160v and 170v, but at 180v the value increases to 1.15698E-05 cm. The average Debye length value for the voltage range from 180v to 220v was 1.20958E-05cm.For 2 ℓ/min gas flow the maximum value for Debye length was 1.81779E-05 cm at 170v. Values for other voltages were calculated as the average value of 1.02697E-05cm. Both 3 ℓ/min and 4 ℓ/min gas flow rates show similar behaviours and close results. Voltages from 150v to 160v have Debye length value that varies from 8E-06cm to 1.2E-5cm. A voltage higher than 150 the Debye length has a value less than 6E-06cm. At 5 ℓ/min gas flow rate the Debye length has the lowest value of 2.86915E-06cm at 150v; this value increases to 8.77561E-05cmat 170v. The average value was 8.99604E-06cm for voltage range from 170 to 220v.

Conclusions:

This paper has evaluated the development which has been made experimentally on plasma parameters induced by Microwave. This was achieved by utilizing OES to determine plasma physical parameters. In addition, this paper studied the influence of applied voltage, argon gas flow rate on the microscopic characteristics (i.e. T_e, n_e, R_t, ω_p, λ_{mfp}, δ, σ_{cd}) were studied as well. It is found that increasing the applied voltage increases the T_e, R_t and δ but decreases the n_e, ω_p and σ_{cd} . In constrict, the increasing in the argon flow rate caused increase in n_e , ω_p and σ_{cd} but decreased the T_e, R_t and δ.
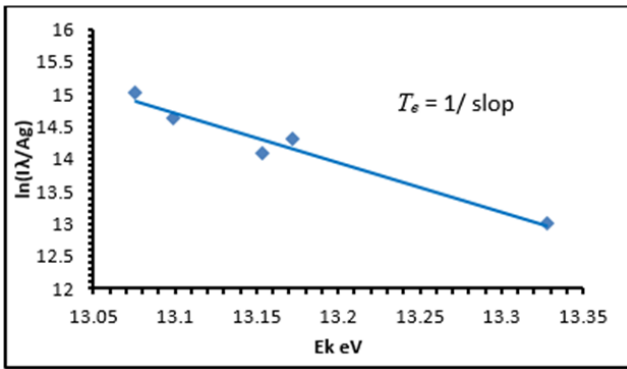
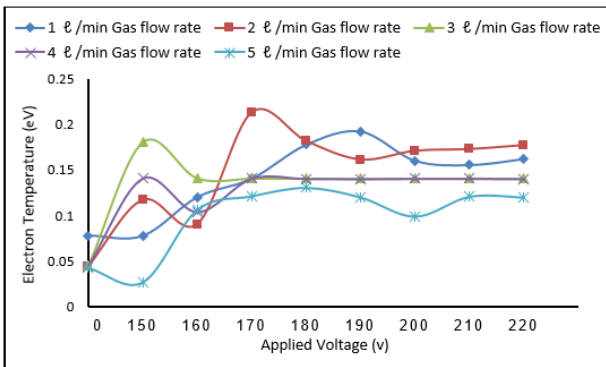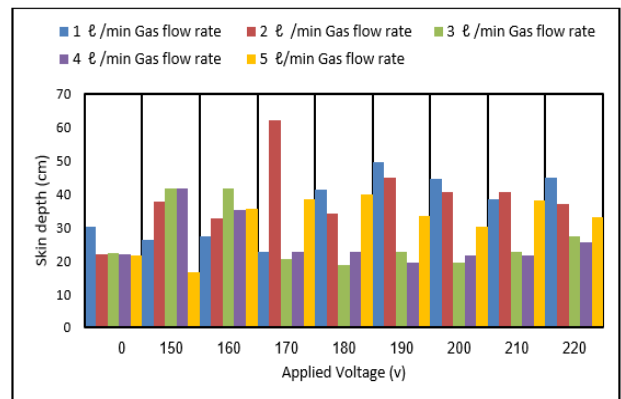**Figure 2. The Boltzmann plot method for single case**

Figure 3. Effect of gas flow rates on the electron temperature and applied voltage.

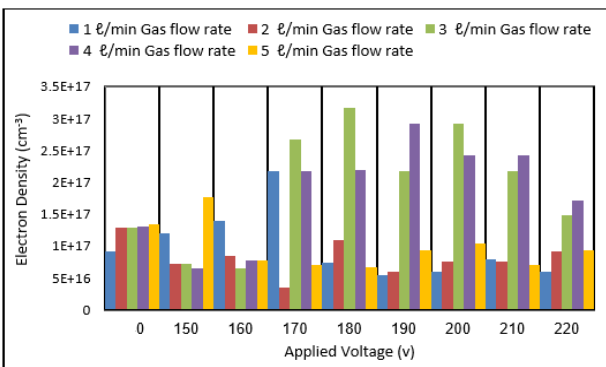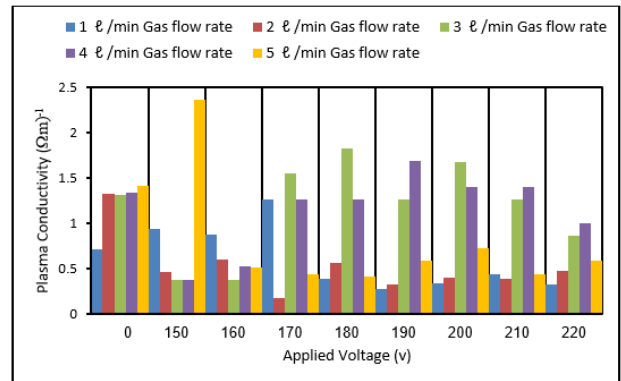**Figure 4. Effect of gas flow rate on the electron density and applied voltage.**

Figure 5. Effect of gas flow rate on the electron residence time and applied voltage.

Figure 6. Effect of gas flow rate on the plasma frequency and applied voltage.

Figure 7. Effect of gas flow rate on the skin depth and applied voltage

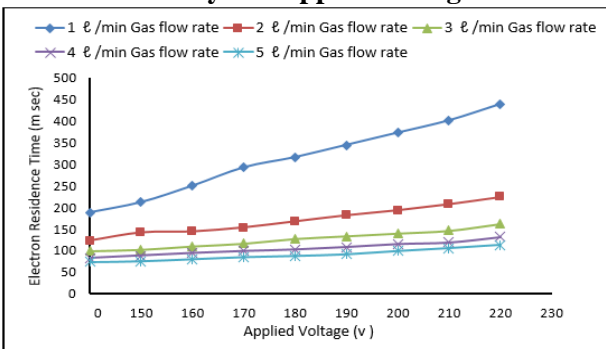**Figure 8. Effect of gas flow rate on the plasma conductivity and applied voltage.**
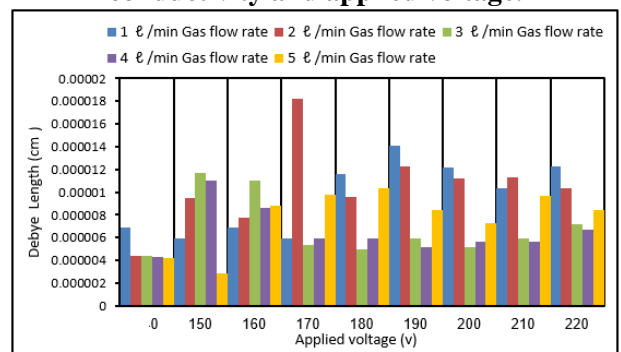

Figure 9. Effect of gas flow rate on the Debye length and applied voltage

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Conflicts of Interest: None.

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تأثير معدل تدفق الغاز على معلمات البلازمـا المنتجة بالامواج المايكروية

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الخلاصة:

تم في هذا البحث بناء منظومة لتوليد البلازما غير الحرارية بواسطة المايكروويف عند الضغط الجوي وعند تردد 2.45 كيكاهيرتز و بقدرة 800 واط. اذ تم استعمال غاز الاركون لتوليد الشعلة بواسطة منظم الجريان. كما تم دراسة تاثير الفولتية المطبقة ومعدل تدفق غاز الاركون على معلمات البلازما المنتجة. تم أستخدام Optical Emission Spectroscopy لدراسة معلمات البلازما مثل درجة حرارة الإلكترون (T_e)، زمن الاعاقة (R_t)، تردد البلازما (ω_{pe})، وعمق الاصطدام (δ)، توصيلية البلازما σ_{dc}، طول ديباي (λ_d). وتم حساب كثافة الإلكترون البلازما باستخدام طريقة Stark broadened.

الكلمات المفتاحية: معلمات البلازما، البلازما المنتجة بواسطة المايكرويف، مخطط بولتزمان، تشخيص البلازما.

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