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Plasma Characterization of Microwave Plasma jet at Atmospheric Pressure

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Abstract
The microwave induced plasma jet (MIPJ) system was built using local materials based on a tapered waveguide. The parameters of this plasma were determined. The other characteristics, such as plasma frequency (fp), Debye length (λ_D), and quantity of particles in the Debye sphere (N_d), electron temperature Te, electron density n_e, and others have been researched as well. The study was conducted at various Ar flow rates between (2.5-10) l/m and different discharge tube inner diameters between (2-10) mm. The MIPJ spectra were used to determine each of these parameters. It was concluded that there is a good chance of influencing MIPJ's parameters by changing these parameters.

Keywords: microwave induced plasma jet, optical emission spectral, electron temperature,

قياس معامل البلازما لموجة الضغط الجوي الدقيقة الناتجة عن نفاثة الأرجون البلازمية

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الخلاصة
تم بناء نظام نفث البلازما الناجم عن الميكروويف (MIPJ) باستخدام مواد محلية وعلى أساس دليل موجي مدبب. تم تحديد معلمات هذه البلازما ، وتشمل الخصائص الأخرى ، مثل تردد البلازما (fp) وطول دي باي(λ_D) وكمية الجسيمات في كرة[دي باي(Nd) ، درجة حرارة الإلكترون Te ، وكثافة الإلكترون ne ، وغيرها لقد تم بحثها كذلك. أجريت الدراسة بمعدلات تدفق Ar مختلفة تتراوح بين (2.5–10) لتر / م وأقطار أنبوب التفريغ بين (2–10) مم. تم استخدام طيف MIPJ لتحديد كل من هذه المعلمات. لقد تقرر أن هناك فرصة جيدة للتأثير على معلمات MIPJ من خلال تغيير هذه المعلمات.

1. Introduction

Plasma is an ionized gas, a mixture of charged particles and neutral atoms ; the term ionized implies the existence of one or more free electrons [1,2]. The parameters of the plasma are determined by the varying features of the radiation entering via the plasma or reflected from it when employing the microwave. The technique does not require anything hypothetical about the nature of the plasma [3]. Electrical discharges caused by electromagnetic waves with a frequency greater than 300MHz are known as microwave discharges. For microwave

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frequencies that are allowed in applications (industry, medicine, and process), it must come to an end at 2.45 GHz. There are now known sources of microwave-induced plasma (MIP).Due to their many advantages, such as the lack of expensive vacuum equipment, inexpensive systems, straightforward systems, and ease of use, they have been studied for decades. Different forms several sources of atmospheric MIP have been created [4].In the 1960s, there was a surge of interest in thermal plasma technology. Industrial applications in the fields of cutting, welding, spraying, , metallurgy, and illumination evolved in the 1970s [5]. The microwave plasma torch can use not just inert gases (such as Ar and He) but also N_2, O_2, and air and has a high coupling efficiency (90%) to focus all microwave power on the plasma contained within a shorted waveguide. Because interference between neighboring torches is insignificant, many can be combined to boost plasma power silently and inexpensively. The microwave plasma torch is made up of the same magnetrons found in regular home microwave ovens. Commercially, these magnetrons are inexpensive, compact, and plentiful. They have a frequency of 2.45 GHz and an average output of roughly 1 kilowatt. To operate home microwave oven magnetrons, a 4 kV electric voltage should be provided to the cathode of the magnetron. A high voltage transformer is used to generate the voltage, which is then rectified using a half-wave voltage doubled circuit. The magnetrons, in other words, run on 60 Hz AC power[6]. Components from the local market were used to build the MIPJ system at the lowest possible cost and to assess its suitability for various uses.

2. Experimental work

Microwave induced plasma jet (MIPJ) system with a simple design was built utilizing low-cost equipment found in local markets. The 2.45 GHz microwave generator (magnetron type (Panasonic- 2M210)) was connected to a taper rectangular waveguide manufactured in the laboratory. The atmospheric MIPJ system that was used in this work is depicted in Figure 1. The taper rectangular waveguide was tapered from one side to 72 mm 5 mm to boost the strength of the electric field in the area of interest to nearly 2.6 times its original value. The discharge tube, a quartz tube with different inner diameter of (2, 6 and10) mm and of 1 mm thickness was placed in a line perpendicular to the waveguide as a substantial wall. The discharge tube was placed 29mm away from the waveguide's shorted end, where the strength of the electric field was most likely at its peak value. Diameter in 10 mm, the discharge tube's bottom side was open to the air away from the waveguide surface.

Table 1: The data that was used in calculating the MIPJ parameters

Ion	Wavelength (nm)	Ag	Ei	Ek
ArI	374.1	3.60E+08	12.12	13.98
ArI	752.4	1.37E+08	12.12	13.98

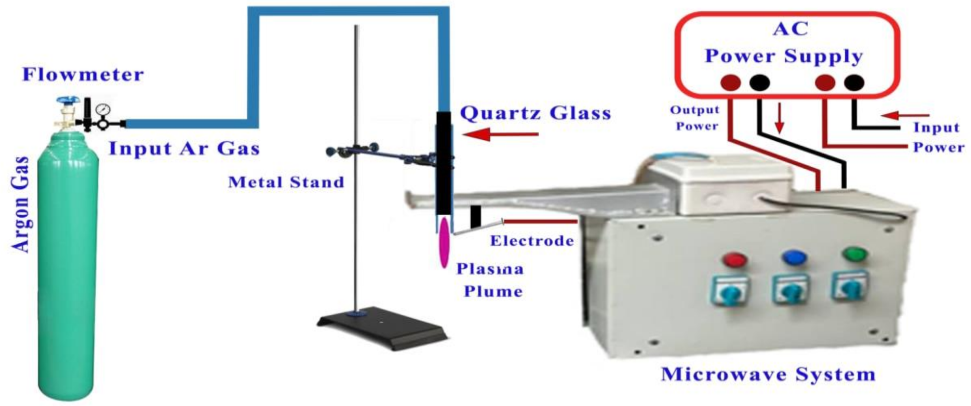

Figure 1: A schematic diagram of the atmospheric MIPJ system

Quantitative and qualitative information, such as the element composition, can be obtained from the plasma spectra. The electron density n_e and the plasma temperature T_e can be determined from the forms, fluctuations, and wavelengths of emission lines [7]. Plasma temperature is a crucial thermodynamic characteristic because it may be used to define and forecast other plasma aspects including relative energy level populations and particle speed distribution.

3-Results and Discussion

3.1- the optical emission spectra

For various Ar flow rates and various discharge tube inner diameters, the optical emission spectra (OES) of MIPJ were recorded. The ratio technique used in this study uses two lines of argon, predicated on the idea that local thermodynamic equilibrium (LTE) has been reached inside the plasma. Within a few hundred nanoseconds of plasma formation, LTE is frequently reached. An efficient way to determine the temperature of the plasma is to compare the intensities of two spectral lines in a spectrum.

The plasma temperature in LTE is determined using Equation (1) for similar ionization stage of an atom or ion[8,9].

$$T = \frac{(E_2 - E_1)}{k\, ln\left(\frac{I_1 \lambda_1 A_2 g_2}{I_2 \lambda_2 A_1 g_1}\right)} \quad (1)$$

Free electrons per unit volume are referred to as electron number density (n_e). The density of electrons can be calculated from the linear Stark broadening of spectral lines. Different widening is disregarded in this work to evaluate the electron number density. The Doppler width of the hydrogen line typically lies between 0.2 and 2 nm. The Stark effect, similar to pressure widening, appears as a result of interactions between radiators and nearby particles. Ion collisions and, to a lesser extent, electron collisions produce these effects in plasma. The Stark effect is principally responsible for the broadening of the hydrogen line used in this experiment [7,10]. The same element's spectral lines and subsequent ionization phases are used in the Saha-Boltzmann equation [9,11]. The Saha-Boltzmann equation is as follows:

$$n_e = \frac{I_1}{I_2^*} 6.04 \times 10^{21} (T)^{3/2} e^{\frac{(E_1 - E_2 - X_Z)}{kT}} \quad (cm^{-3}) \quad (2)$$

Where

$$I_2^* = \frac{I_2 \lambda_2}{g_2 A_2} \tag{3}$$

T_e is the electron temperature. X_z is the ionization energy of the species during the ionization stage z in eV, z represents the species' ionization phase for the reference. The plasma frequency is calculated by Equation (4) [15]:

$$f_p \approx 8.98 \sqrt{n_e} \ \text{(Hz)} \tag{4}$$

The frequency of plasma is one of its most important features, and it is exclusively determined by the plasma density [12].The response of charged particles to reduced local electric field is known as Debye shielding, and it is this shielding that gives plasma its quasi-neutrality. The definition of λ_D, also known as the Debye length [13]:

$$\lambda_D = \left(\frac{\varepsilon_o k T_e}{n_e e^2} \right)^{1/2} = 743 * (T_e / n_e)^{½} \tag{5}$$

n_e is the electron number density, K is the Boltzmann constant, and λ_D is the Debye length in centimeters. The electron charge is e (C), while the electron temperature is Te. N_D refers to the number of particles in the Debye sphere, which is determined by electron density and temperature. The second requirement for plasma existence is that $N_D >>> 1$ [13]:

$$N_D = \frac{4\pi}{3} n_e \lambda_D^3 \tag{6}$$

The OES for MIPJ were recorded for varied flow rates and different discharge tube inner diameters, as shown in Figures (2), (3) and (4). From These figures, it can be noted that the diameter does not affect the peaks intensity when the flow rate is constant. Also the lines of ionizing elements ArI, ArII, NiI, NiII are clear in these spectra.

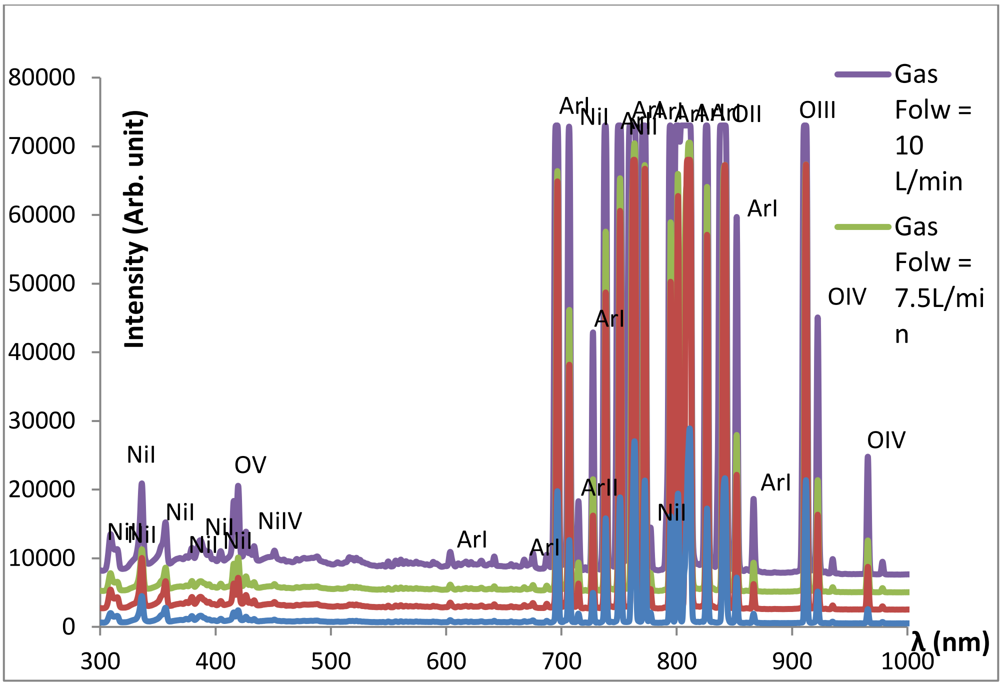

Figure 2: OES for MIPJ at (10 l/m) Ar flow rate and (10mm) discharge tube inner diameter.

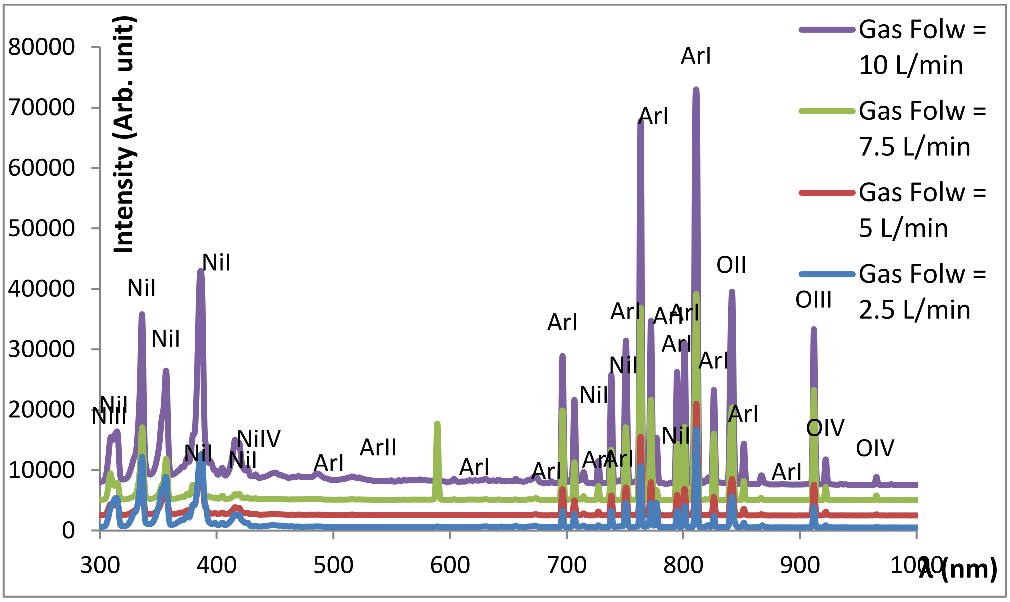

Figure 3: OES for MIPJ at (10 l/m) Ar flow rate and (6mm) discharge tube inner diameter.

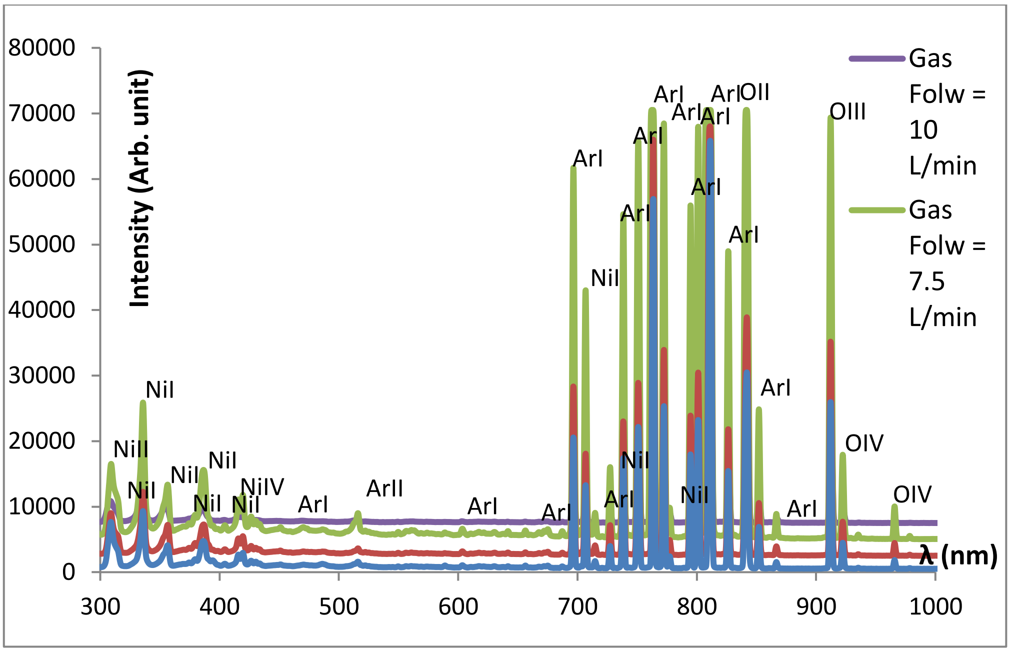

Figure 4: OES for MIPJ at (10 l/m) Ar flow rate and (2mm) discharge tube inner diameter.

From Figures (2), (3) and (4), it is noted that as the gas flow increases, the intensity of the spectral lines of the gas increases.

The number of ionic lines is greater than the number of lines resulting from ionized atoms or ionized molecules because the energy of irritation of atoms is less than the ionization energy because when the energy increases, the irritation between atoms decreases

3.2 Calculation of electron temperature and electron number density

Figures (5), (6), and (7) show the influence of gas flow rate on the electron temperature (Te) and electron number density(n_e) at different tube diameters. The ratio technique was used to visualize the amplitude of the obtained spectrum distribution against wavelength using two lines of Ar gas (374.1,752.4 nm) and the NIST dataset [14] and the OES in Figures (3,4 and 5). The Saha–Boltzmann (Equation (2)) was utilized in Equation (1). T_e and n_e increased in the cold plasma system with increasing flow rate, as demonstrated in the line graph. Table (2) shows the change of T_e and n_e with the change of the gas flow rate and the discharge tube inner diameter.

Table 2: The effect of the discharge tube inner diameter and the gas flow rate on T_e and n_e.

diameter (mm)	gas flow rate (l/min)	T_e (ev)	n_e (cm^{-3})
10	2.5	1.490	8.8×10^{18}
	10	1.900	38.5×10^{18}
6	2.5	1.410	5.7×10^{18}
	10	1.810	28.1×10^{18}
2	2.5	1.370	4.5×10^{18}
	10	1.730	20.7×10^{18}

This behavior can be interpreted as follows: when the gas flow rate increases, it causes an increase in the number of collisions between the electrons and the gas atoms. As a result, the energy transferred from the electrons to the gas molecules increases causing the gas temperature to increase by increasing the electron temperature. Also, in argon plasma, electron impact is thought to be the primary mechanism for excitation and ionization of atomic and ionic species. The high-energy tail of the electron energy distribution function contracted to lower energies as the gas flow rate rose. As a result, direct ionization, which occurs when an energetic electron collides with gas atoms, is minimized. From Figure (4), it can be observed that the number of electron density increases when the flow rate increases due to the stepwise ionization [16].

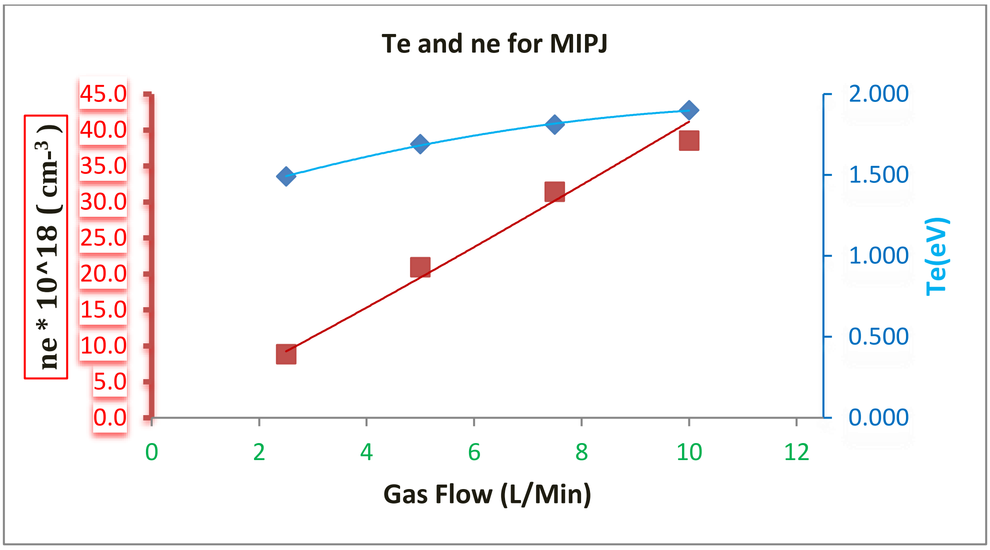

Figure 5: MIPJ electron temperature Te and density as a function of gas flow rate for (10mm) discharge tube inner diameter.

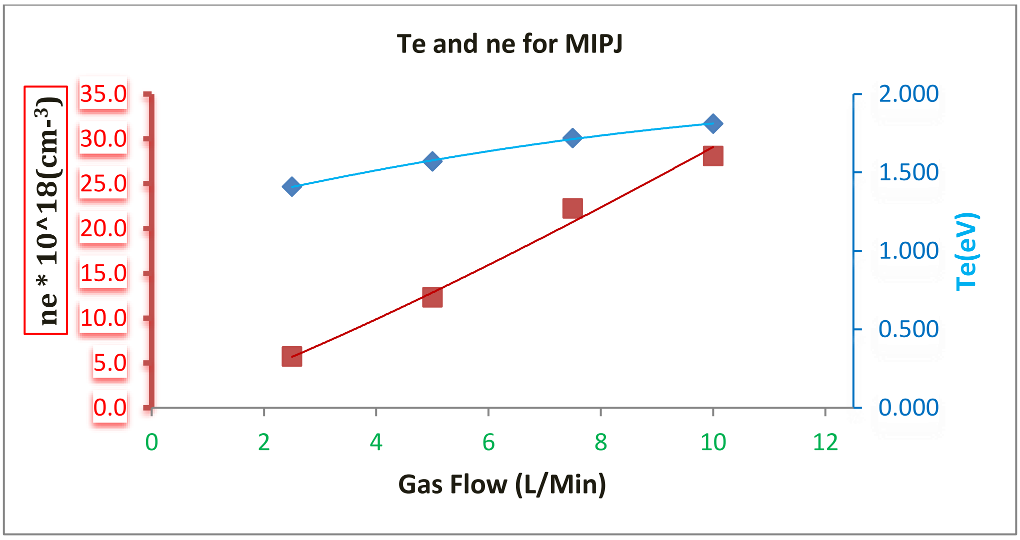

Figure 6: MIPJ electron temperature Te and density as a function of gas flow rate for (6mm) discharge tube inner diameter.

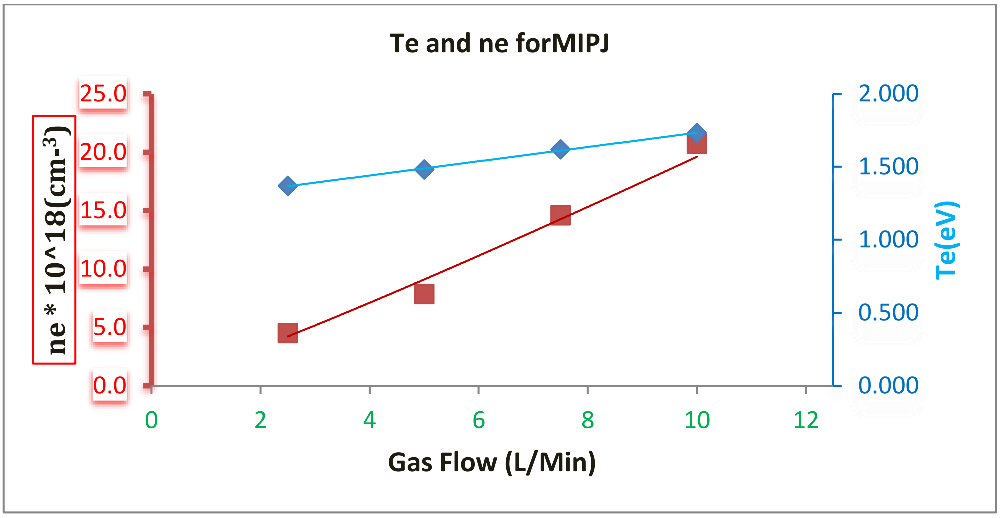

Figure 7: MIPJ electron temperature Te and density as a function of gas flow rate for (2mm) discharge tube inner diameter

Tables (3, 4, 5) show the electron number density (n_e) that has been calculated using Equation (2), electron temperature (T_e)calculated by Equation (1), plasma frequency (fp) calculated according to Equation (4), and Debye length (λ_D) and plasma parameter (N_D) as calculated by Equation 5 and 6, for the different discharge tube inner diameter.

Table 3: MIPJ parameters at different Ar gas flow rates (l/min) at (10 mm) discharge tube inner diameter.

Gas Flow (l/min)	Te (eV)	n_e (cm^{-3})	f_p (Hz)	λ_D (cm)	N_D
10	1.280	2.00E+18	1.3E+13	5.5E-05	1.4E+06
7.5	1.020	2.52E+17	4.5E+12	1.4E-04	2.8E+06
5	0.810	1.79E+16	1.2E+12	4.6E-04	7.5E+06
2.5	0.730	4.67E+15	6.1E+11	8.6E-04	1.3E+07

Table 4: MIPJ parameters at different Ar gas flow rates (l/min) at (6 mm) discharge tube inner diameter.

Gas Flow (l/min)	Te (eV)	ne (cm-3)	fp (Hz)	λ_D (cm)	N_D
10	1.810	2.81E+19	4.8E+13	1.8E-05	6.3E+05
7.5	1.720	2.22E+19	4.2E+13	1.9E-05	6.6E+05
5	1.570	1.23E+19	3.2E+13	2.5E-05	7.7E+05
2.5	1.410	5.72E+18	2.1E+13	3.4E-05	9.6E+05

Table 5: MIPJ parameters at different Ar gas flow rates (l/min) at (2mm) discharge tube inner diameter.

Gas Flow (l/min)	Te (eV)	ne (cm-3)	fp (Hz)	λ_D (cm)	N_D
10	1.730	2.07E+19	4.1E+13	2.0E-05	6.9E+05
7.5	1.620	1.46E+19	3.4E+13	2.3E-05	7.4E+05
5	1.480	7.87E+18	2.5E+13	3.0E-05	8.8E+05
2.5	1.370	4.52E+18	1.9E+13	3.8E-05	1.0E+06

4-Conclusions

In this work, MIPJ system with a simple design was built utilizing low-cost equipment found in local stores. It was used in the laboratory to construct a taper rectangular waveguide that would allow the system to function with atmospheric pressure. OES was used to characterize the MIPJ system in order to identify the plasma parameters such as electron temperature (Te) using Saha equation, electron density (n_e), Debye length (λ_D) and other parameters. This research led to a conclusion about the possibilities for creating MIPJ systems, diagnosing them, and judging their suitability for various applications.

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