

Research Article

## Effect of Gas Flow Rate on The Electron Temperature, Electron Density and Gas temperature for Atmospheric Microwave Plasma Jet

Hammad R. Humud<sup>†\*</sup>, Qusay A. Abbas<sup>†</sup> and Aws F. Rauuf<sup>‡</sup>

<sup>†</sup>Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq

<sup>‡</sup>Ministry of Science and Technology, Materials Researches Directorate, Baghdad, Iraq

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### Abstract

*In this work, parametric observations of atmospheric argon plasma excited by 2.45 GHz microwaves in an open-ended Pyrex tube are reported. Microwave power, discharge tube dimensions and argon flow rate were the major operating parameters. Electron temperature and electron density for argon plasma were measured by optical emission spectroscopy (OES) for gas flow rates (1, 2.5 and 5)  $\ell\text{min}^{-1}$  and 850W of microwave power. The electron temperature was measured using Boltzmann plot method and ranged (2700-1761)K for above gases flow rates. The electron density that obtained by Stark broadening were ranged ( $1.6 \times 10^{17}$  -  $2 \times 10^{17}$ )  $\text{cm}^{-3}$ . The electron density increased when gas flow rate was increased while, The electron temperature decreased when gas flow rate was increased. Gas temperature measured using infrared thermometer with five values of gas flow rate (1, 2.5, 5, 7.5 and 10)  $\ell\text{min}^{-1}$  and ranged (32-60)  $^{\circ}\text{C}$*

**Keywords:** Microwave plasma jet, tapered waveguide, plasma parameters.

### Introduction

Atmospheric microwave induced plasma (MIP) sources have been studied for decades due to their many advantages, such as the lack of the necessity for expensive vacuum equipment, low cost, simple systems and easy operation. Because of these advantages, many types of atmospheric MIP sources have been developed. In particular, the Microwave Continuous Flow Reactor (MCFR) (Roth, 1995), Surface Wave Sustained Plasma (SWSP) (Moisan *et al*, 1992), Torch with Axial gas Injection (TIA) (Moisan *et al*, 1994), Microwave Plasma Torch (MPT) (Krzysztof and Adrianna, 2007) and Microwave Cavity plasma are well-known types of plasma sources using microwaves. The main application areas for these plasma sources have been in real-time metal emission monitoring (Woskov *et al*, 1996), atomic spectrometry, etching, cleaning, plasma chemistry, surface modification, cutting, thin film technology (Ezzat, 2015), textile and remediation of gases (Mizeraczyk *et al*, 2012) and medicine (Ermolaeva *et al*, 2012) as well as atmospheric pressure plasma source have been utilized as a tool for modifying polymer and metal surfaces (Okamoto, 1996). For diagnostics optical emission spectroscopy (OES) used as one of the alternative diagnostics because of its simplicity and non-intrusive nature (Lebedev, 2010). This work

concerns on atmospheric microwave-induced plasma jet (MIPJ) generated in ambient air by an argon discharge sustained in an open-ended of Pyrex discharge tube. In this work, the electron temperature was measured as well as the electrons density by OES for local-made atmospheric microwave plasma jet system of a simple design.

### Experimental work

A simple design of microwave induced plasma jet (MIPJ) system was built using a low cost equipment which available in local markets. (MIPJ) system was consists of 2.45 GHz microwave generator (magnetron type (Panasonic- 2M210)) connected with waveguide type WR-284 and field applicator. Fig.1 shows a schematic diagram of the atmospheric (MIPJ) system that built in our lab. The rectangular waveguide type (WR-284) was tapered from one side to 72 mm  $\times$  5 mm to increase the electric field strength in the region of interest to about 2.6 times (Bae, 2006). A Pyrex tube of 4 mm inner diameter and thickness of 1mm was inserted perpendicularly to the wide wall of the waveguide and served as a discharge tube. The discharge tube was located at 29mm away from the shorted end of the waveguide where the electric field intensity is probably at its maximum. The bottom side of the discharge tube was open to the air away from the waveguide surface in 10 mm.

\*Corresponding author: Hammad R. Humud

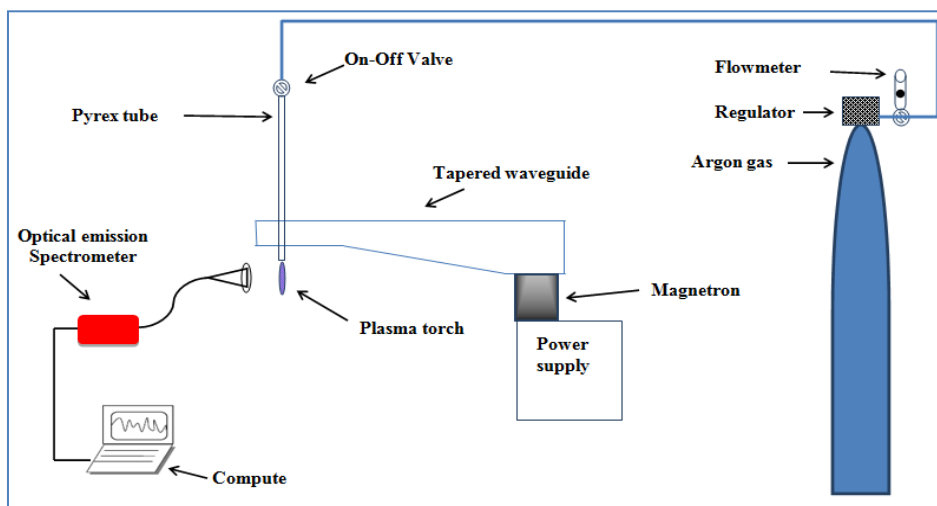


Fig.1: A schematic diagram of the atmospheric MIPJ system

Table 1: Spectroscopic data of argon lines used for OES diagnostic (Griem, 1997)

| Ion | Wavelength (nm) | $A_k \times 10^6 (s^{-1})$ | $E_i$ (eV) | $E_j$ (eV) | $g_j$ |
|-----|-----------------|----------------------------|------------|------------|-------|
| 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     |

All the measurements were performed under the same experimental conditions except that the gas flow rate and microwave power were varied. The spectrometer used for the OES was (THORLABS CCS 200) with a 600 Lines/mm, 800 nm Blaze grating. The entrance slit width was maintained at 50  $\mu$ m,

**Results and Discussion**

The electron temperature of ArI lines was measured using the Boltzmann plot method. The atomic emission intensity ( $I_{ji}$ ) of the transition from level  $j$  to level  $i$  depends on the transition probability ( $A_{ji}$ ) and absolute population of the atomic level ( $N_j$ ), as shown in the following equation:

$$I_{ji} = \frac{hc_0}{4\pi\lambda_{ji}} A_{ji} N_j \tag{1}$$

where  $\lambda_{ji}$  is the wavelength of the emitted light,  $h$  is the Planck's constant ( $6.626 \times 10^{-34}$  J. s),  $c_0$  is the velocity of light in vacuum ( $3 \times 10^8$  m/s), and  $A_{ji}$  is the transition probability, which is the probability per second that an atom in state  $j$  spontaneously emits in a random direction and is de-excited to state  $i$ . Assuming a Boltzmann distribution of the population of the atomic level, the emission intensity is expressed (Kuo, 2006).

$$\frac{I_{ji}\lambda_{ji}}{A_{ji}g_j} = \frac{hc_0N}{4\pi Z(T)} \exp\left[-\frac{E_j}{k_B T_e}\right] \tag{2}$$

where  $N$  is the number density of bound electrons in all ionization states,  $Z(T)$  is the partition function,  $\lambda_{ji}$  is the

wavelength of the corresponding transition,  $g_j$  is the statistical weight of level  $j$  and  $E_j$  is its energy in  $cm^{-1}$ ,  $k_B$  is the Boltzmann constant, and  $T_e$  is the electron temperature in Kelvin. by taking the logarithm in both sides of equation (2):

$$\ln\left(\frac{I_{ji}\lambda_{ji}}{A_{ji}g_j}\right) = -\frac{E_j}{k_B T_e} + Constant. \tag{3}$$

Several spectral lines are considered (represent ArI); all of these lines have a similar lower energy level  $E_i$  with different upper energy level  $E_j$ . In this study, five lines have been taken (696.54, 763.51, 772.37, 801.47 and 811.53) nm. Table 1 lists argon lines considered with their spectroscopic data (Griem, 1997).

By substitute the values of  $E_j$ ,  $A$  and  $g_j$  for the five lines ArI in the equation (3) and 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, the electron temperature  $T_e$  which is related to the slope of the linear fitting can estimate as shown in Fig.2 (Wasfi at el, 2015).

The electron density was measured by the Stark broadening width of the line 696.45 nm that is emitted from the argon plasma. This broadening of ArI (696.54nm) line is obtained through the de-convolution of Voigt profile by using non-linear curve fitting and is used to determine the electron density by using the following relation (Griem, 1974; Tu et al, 2007):

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

$$\text{then } n_e = \exp\left(44.2476 + 1.20 \ln \Delta\lambda_{\frac{1}{2}} - 0.6 \ln T_e\right) \quad (4)$$

where,  $T_e$  is the electron temperature in K and  $n_e$  is the electron number density in  $\text{cm}^{-3}$  and  $\lambda_{1/2}$  is the line width at half maximum intensity of line (696.54 nm). Using Boltzmann method for three cases of argon gas flow rate (1,2.5 and 5)  $\ell\text{min}^{-1}$  at fixed microwave power 850 W and 4 mm inner diameter Pyrex tube one can observe that the electron temperature decrease when gas flow rate was increase. In other hand, the values of electron densities for same conditions of gas flow rate and microwave power showed increasing when flow rates increasing, both Figs.3 and 4 illustrate that's behavior of electron temperatures and electron densities with the gas flow rate. 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 particles increases causing an increase in the gas temperature by lowering the electron temperature. Also, the mechanism of excitation and ionization of atomic and ionic species in argon plasma is supposed to occur mainly by electron impact. When the gas flow rate increased, the high-energy tail of the electron energy distribution function was contracts to the lower energies. Therefore the direct ionization, which results from the energetic electron's impact with gas atoms, is reduced but in Fig.4 it can observe that the number of electron density increasing when flow rate increasing due to the stepwise ionization.

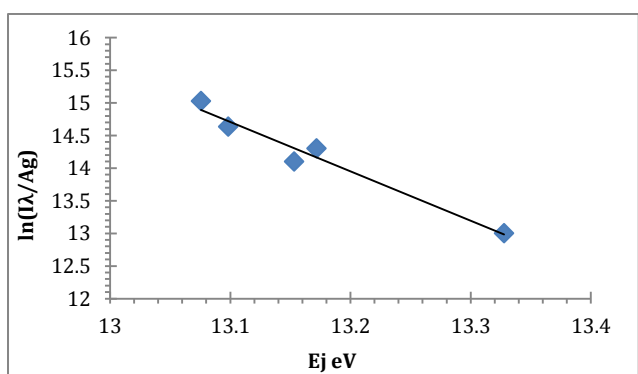


Fig.2: Boltzmann plot to determine the electron temperature

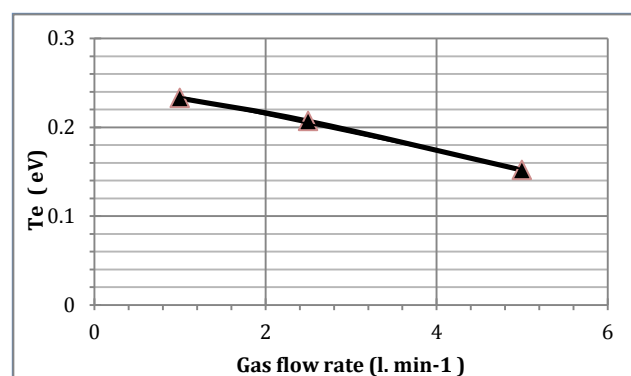


Fig.3: Electron temperature verse gas flow rate

To determine the temperature of the working gas, that jetted away of the Pyrex tubes, a silicon wafer fixed about 5 cm away from the open end of the tube to heated it by the torch flam for several minutes until reaches the saturation, while an infrared thermometer recorded the temperature of the wafer as a function of the time. This simply method used to determine the silicon wafer temperature as a function to plasma gas temperature.

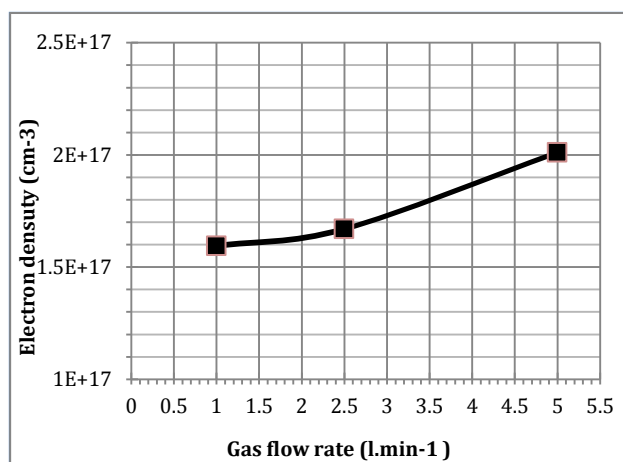


Fig.4: Electron density verses gas flow rate

Fig.5 shows the rising of the silicon with the time, it can see that the wafer temperature increase with time until it was reach a saturation point which refer to the real temperature of gas. in this work our plasma did not exceed the 60 °C at the examined distance, that's results open the way to many applications that's deal with sensitive surfaces to the heating such as human tissue and polymers .

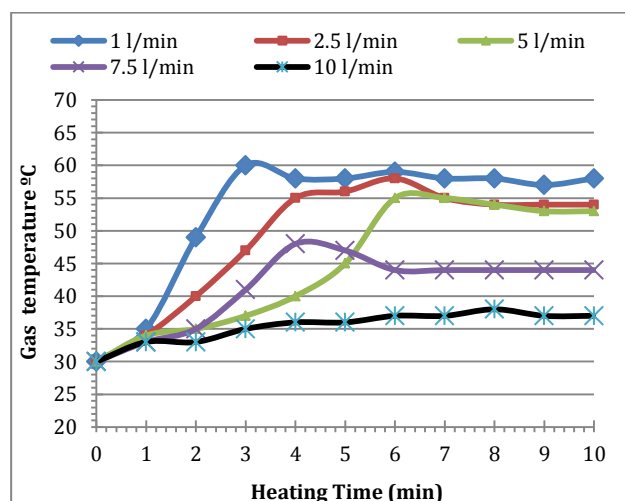


Fig.5: Gas temperature as a function to the heated time with different flow rates

Its cleared that the temperature of the gas decrease when the gas flow rate increase, that's improve the fact that increasing gas flow rate cool down the plasma (Moon, 2002).

## Conclusions

The Boltzmann plot methods and Stark broadening can be used successfully to determine the electron temperature and density in atmospheric induced argon plasma jet. Basic motivation of this study is to explore the effects of gas flow rate on the excitation and ionization process involved in optical emission. Experimental results show that the electron temperature decreases when the gas flow rate increase and the electron density increases when gas flow rate increasing. In other hand this system can successfully produce plasma temperature did not exceed 60 °C which can used in many applications.

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