Influence of Gas Flow Rate on Plasma Parameters Produced by a Plasma Jet and its Spectroscopic Diagnosis Using the OES Technique

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ABSTRACT: In this study, the emission spectra of plasma generated from the argon gas in a plasma jet system were measured under normal atmospheric pressure, at constant voltage and for different flow rates from 1–5L/min. The plasma parameters were calculated based on electron density, frequency of plasma, the temperature of an electron, Debye length and the number of particles in the Debye sphere. We employed optical emission spectrometer (OES) technology, which captured the spectrum resulting from the plasma at various flow rates of argon gas. While the flow rate of argon gas to the plasma generated from the discharge current (D.C.) increased, the ranges of the temperature and density of the electron (Tₑ) were 0.075–0.1eV and 6.15–9.75x10⁷cm⁻³, respectively. In contrast, a rise in the intensity of spectral lines was observed.

Keywords: argon gas; Debye length, OES, plasma jet, plasma parameters

1. Introduction:

Plasma is usually a quasi-neutral gas of charged and neutral particles that exhibits collective behaviour, which incorporates charged particles (electrons, ions, and molecules). The word ‘ionised’ refers to the life of a free-electron but does not refer to an atom or molecule. Plasma has free charging particles with both the negative and positive charges storing roughly at the macroscopic stage. This occurs when the elements for a particular state of matter are heated to a temperature that is higher than thermal energy and above binding energies [1]. A diagnostic of the plasma aims to get information about plasma parameters using various experimental methods. It is necessary to know the characteristics of plasma to understand the impacts of the various physical proceedings that take place and to determine plasma properties from these proceedings. Such diagnostics include electrical samples and optical spectroscopy of emissions [2].

Typically, only probes are regularly used to measure the density and temperature of ion and electrons. Nevertheless, in magnetised or deposited plasmas, analysing the characteristics of the probe is challenging and may lead to incorrect results [3].

Spectroscopic methods, for instance, dispersion of laser, emission, absorption or spectrometry of fluorescence are specific methods of sampling different pieces of plasma in the absence of disrupting its status and structure [4]. Optical emission spectroscopy (OES) is one of these techniques [5]; it depends on the calculation of the optical radiation released from the plasma because it represents plasma properties in the chemical, molecular and ionic radiator’s immediate environment [6]. The electrons or ions interact with the other particles of the plasma that give radiation. Electron interactions tend to take control of the procedures and the excitation of collision and ionisation because of their high velocity. Three electron transitions can take place during these interactions: boundary transitions, significant transitions and free transitions. As a consequence of these transformations, emitted light forms a band, line or progressive
spectra. When the electrons pass with various levels of energy into the atomic system, the ions and atoms for active gas and trace defects emit radiation. Contrary to continuum radiation in the free-electron, for example, bremsstrahlung, the emission is in the form of short spectral lines [7].

Under atmospheric pressure discharge conditions, non-equilibrium plasmas can be produced, most of which can be handled significantly. These discharge plasmas can be generated at the liquid state, where the numbers of applied fields increase, as in the medical, food, agricultural and textile industries [8–11].

McWhirter [12] suggested four plasma models based on the mechanism of electron interaction. These models are local-thermal-equilibrium (LTE), stable-state corona, time-dependent corona and collision radiative. For low-density plasmas, spontaneous decay balances the collisional excitation and radiative recombination balances collisional ionisation. The population densities of the new rates are calculated for such low-density plasmas from a balance between radiative decay to ground state and collisional excitations [13].

The temperature of the plasma is a significant thermodynamic property because of its ability to identify and forecast specific characteristics of plasma; for example, populations with particle velocity distribution and relative energy levels. The two-line hydrogen ratio approach is utilised in this laboratory experiment. The ratio is a common way of measuring the temperature of plasma that can be determined by the intensity ratio for a pair of atom spectral lines or ions of a similar level of ionisation [14]. For LTE, the electron temperature (T) eV is determined from the equation below [15]:

\[
T_e = \frac{-(E_{l1} - E_{l2})}{k \ln \left( \frac{I_{l2} \lambda g_{l2} A_{l2}}{I_{l1} \lambda g_{l1} A_{l1}} \right)} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldot
level -2 to level -1, $g_2$ is the statistical move weight from level -2, $A_2$ is the transition eventuality from level -2 to level -1 and the subscript z denotes the species ionisation stage for the referred species [21].

The frequency of plasma is determined from the following equation [22]:

$$f_p = 8.98\sqrt{n_e} \text{(Hz)} \quad \ldots \ldots \quad (4)$$

This frequency, which only depends on density, is one of the basic parameters of plasma. Plasma frequency is usually very high due to the small mass of electrons [22].

A charged particle reaction that decreases the impact of electric on local fields is named Debye shielding ($\lambda_D$), where the shielding accords the plasma its property of quasi-neutrality. The distance ($\lambda_D$) can be named as the length of Debye, which was previously described as [23]:

$$\lambda_D = \frac{\varepsilon_0 K_B T_e}{n_e e^2} = 743 \times \frac{T_e}{n_e} \ldots \ldots \quad (5)$$

Debye length should be minimal when compared to the system dimension. This first condition for plasma existence is described as follows [24]:

$$\lambda_D \ll L$$

$L$ is the system dimension (cm) and $N_D$ represents the particles' number density on the surface of Debye based on the density and temperature of the electron. This second condition for plasma existence $N_D \gg 1$ is as follows [25]:

$$N_D = \frac{4\pi}{3} n_e \lambda_D^3 \quad \ldots \ldots \quad (6)$$

The specific number of particles in a Debye sphere is given by plasma parameter [26]:

$$\Lambda = 4\pi n_e \lambda_D^3 = \frac{1.38 \times 10^9 T_e^3}{n^2} \quad \ldots \ldots \quad (7)$$

where $\Lambda$ is the plasma parameter?

In this paper, Ar plasma is described in terms of argon fraction and operating parameters utilising OES to investigate the production of active species. The electron temperature, which also influences the plasma reactivity through inelastic collisions producing the active species, is evaluated from ArI spectral line intensities using the Boltzmann plot method. The key aims of this paper are to underpin the plasma reactivity species and to achieve a better understanding of the mechanisms regulating the development of these species.

2. Experimental section

2.1 Plasma jet system

An atmospheric plasma jet was used to produce cold plasma with various flow rates of argon gas at a constant voltage. The plasma system consists of the following parts:

- Argon gas: to generate cold plasma.
- Gas flow meter: to monitor the gas intake that connects to the hollow metal tube with a calibrator of 1–5 L/min.
Hollow metal tube: stainless steel tube that is 3 cm long with an internal diameter of 2 mm.

Power supply (D.C.): high voltage between 10 and 20 kV and a cut frequency of 25 kHz.

2.2 Experiment setup

Figure 1 illustrates the work steps for this research.

Figure 1 Diagram of the experiential framework of the plasma jet

The 3 cm-long hollow metal tube is made of stainless steel with an internal diameter of 2 mm. This metal tube is connected to the anode electrode of the high-voltage power supply. It has a flat end measuring 1 × 1 cm, and the spectrum is recorded for different flow rates of argon gas (1–5 litres per minute). Figure 2 shows a schematic diagram of the plasma jet configuration.

Figure 2 Device design for the plasma jet and OES technique

The spectrometer has a high resolution and responds with 3,648 pixels to a wavelength between 200–900 nm. The spectrum of Ar plasma was obtained within a wavelength of 690–780 nm for each flow rate of gas (1–5 L/min).

Eventually, the data from the National Institute of Technology and Standards (NIST) database was analysed and measured [27]. The parameters and characteristics of the plasma were determined afterwards.
3. Results and discussion

3.1 Evaluation of plasma parameters

3.1.1 Optical emission spectroscopy

Plasma emissions with different flow rates produced by atmospheric pressure in the plasma jet system were recorded. The resulting distribution of the spectrum was then plotted as amplitude against wavelength. The spectra of the optical emission of argon gas to generate cold plasma were recorded using the OES technique. A spectrum consists of several characteristic spectral lines of a particular atom and ions of Ar. Figure 3 shows the emission spectra of argon gas to generate cold plasma in a fundamental wavelength with a spectral range of 690–780 nm and flow rates of 1–5 L/min, in comparison with sharp standard lines for ArI and ArII [28]. The optical emission spectra of Ar were measured using the OES technique for the cold plasma. Figure 3 demonstrates that the peak flow rate of argon has an essential and robust effect on emission line intensities, where the intensities of the spectral lines increase with the increasing gas flow rate as more molecules are passing through the tube. Most of the gas molecules passing through the plasma needle ionise the gas passing through the state of the plasma, which leads to an increasing number of excited atoms and, hence, the peaks of spectral line intensities.

![Emission spectra Ar gas to generate cold plasma at atmospheric pressure with different gas flow rates](image)

**Figure 3** Emission spectra Ar gas to generate cold plasma at atmospheric pressure with different gas flow rates

For temperature measurements, the lines were taken at 696.73, 738.31 and 774.50 nm. Figure 4 shows the Boltzmann plot where the electron temperature is equal to the reverse of the slope of the fitting line. $R^2$ is a statistical coefficient that indicates the interest of the linear fit and takes a value between 0 and 1, with the best having an $R^2$ value closer to 1. Figure 5 demonstrates the Gaussian curve fitting of the ArI line and the variation of the FWHM broadening with different flow rates.
Figure 4 Boltzmann plot for argon gas with different flow rates: (a) 1 L/min, (b) 2 L/min, (c) 3 L/min, (d) 4 L/min, (e) 5 L/min
3.1.2 Determination of temperature and density of the electron

The temperature of the electron ($T_e$) was measured from the line strength ratio using Eq (1); spectra from the OES were considered and the corresponding values of different parameters were taken from the NIST database [27]. The densities of the electrons were determined using Saha–Boltzmann in Eq (2) and the measured electron temperature.

The line graph in Figure 6 illustrates the influence of the change of gas flow rate on the temperature ($T_e$) and the density ($n_e$) of the electron. It is clear from this line graph that $T_e$ and $n_e$ increase gradually with an increased flow rate in the cold plasma system [28]. It is also shown that electron temperature and density at 1 L/min flow rate are 0.075 eV and $6.15 \times 10^{17}$ cm$^{-3}$, whereas at 5 L/min the values are 0.10 eV and $9.75 \times 10^{17}$ cm$^{-3}$, respectively.
Figure 7 a, b and c show that the Debye length ($\lambda_D$) and plasma parameters ($\Lambda$) decrease. In contrast, the plasma frequency ($f_p$), and Debye number ($N_D$), increases with an increase in Ar gas flow rate because it is proportional with $n_e$.

![Graph](image1)

![Graph](image2)

![Graph](image3)

![Graph](image4)

**Figure 7** Determination of (a) Debye length($\lambda_D$), (b) Debye number ($N_D$), (c) plasma parameters ($\Lambda$), (d) plasma frequency ($f_p$) as a function of different gas flow rates

Table 1 shows the $T_e$, $n_e$, $\lambda_D$, $f_p$, $N_D$, and $\Lambda$ for Ar gas at different flow rates. Criteria plasma were achieved through the results of the plasma parameters ($\lambda_D$, $\Lambda$), which showed a decrease with increasing flow rate because it is proportional to $n_e$. In contrast, $f_p$ and $N_D$ had an opposite (decreasing) trend. This agrees with the results reported by a previous study [29].
Table 1 Plasma parameters for Ar gas with different flow rates (L/min)

| Flow rate (L/min) | FWHM | T_e (eV) | n_e×10^{17} (cm^{-3}) | f_p×10^{12} (Hz) | λ_D×10^{-5} (cm) | N_d×10^{3} | A |
|------------------|------|----------|------------------------|------------------|------------------|-----------|---|
| 1                | 0.820 | 0.07558579 | 6.15                   | 7.042289826 | 0.259426442     | 4.5E+01  | 175.4798 |
| 2                | 1.000 | 0.07980846 | 7.5                    | 7.776908126 | 0.244418178     | 4.6E+01  | 156.8736 |
| 3                | 1.060 | 0.086730269| 7.95                   | 8.006816971  | 0.242890729     | 4.9E+01  | 145.7999 |
| 4                | 1.200 | 0.09491268 | 9                      | 8.519176016  | 0.241393489     | 5.2E+01  | 132.5036 |
| 5                | 1.300 | 0.105042017| 9.75                   | 8.867039529  | 0.24031041      | 5.8E+01  | 134.8676 |

4. Conclusion

It has been concluded that the intensity of the emission spectrum lines of cold plasma generated by a plasma jet highly depends on environmental conditions. The investigation showed that the increase in the flow of argon gas leads to an increase in the intensity of emission, implying an increase in the number of gas molecules. This indicates that the energy supplied to the particles by the electrolyte field is sufficient to cause secondary ionisation of the molecules, thus, ionising most of the gas molecules passing through the plasma tube. Therefore, the passing gas turns into a plasma state, so the intensity appears at the lowest peak at a flow rate of 1 L/min, whereas it seems that its highest peak is at a flow rate of 5 L/min. We conclude from this that an increase in the gas flow rate contributes significantly to the effects on the plasma parameters of the density and temperature of an electron, Debye length, the frequency of plasma and the number of particles on the surface of Debye, which increases with an increased gas flow rate.

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