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/Effect of Gas Flow Rate on Spectral Properties of Magnetically Stabilized Gliding Arc Discharge Plasma.

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Abstract

In this paper, the Magnetically Stabilized Gliding Arc Discharge (MSGAD) system was constructed to produce non-thermal plasma using argon gas under atmospheric pressure. A gliding plasma discharge was stabilized by a magnetic field for the purpose of a planned investigation. The emission spectra of the generated plasma using a gliding arc discharge system were recorded under atmospheric pressure, with a constant value of alternating voltage (4 kV) and at different gas flow rates of(0.5–2.5)L/min. The plasma parameters, including electron temperature (T_e), electron density (n_e), plasma frequency, Debye length and electron temperature, were calculated. The electron temperature was measured using the Boltzmann plot method, and the electron density was determined using the Stark broadening method. The results show an increase of the electron temperature from 1.138 to 1.277eV and electron density from 2.78×10^{17} to 3.48×10^{17} cm^{-3} as the gas flow increased from 0.5 to 2.5 L/min. Also, the spectral line intensity increases with the increase of the gas flow rate.

Keyword: Magnetically1stabilized gliding1arc discharge, gliding arc discharge, Plasma parameters, Plasma diagnostic, Optical emission spectroscopy.

تأثير معدل تدفق الغاز على الخصائص الطيفية للتفريغ القوس الانزلاقي المستقر مغناطيسياً

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الخلاصة

في هذا البحث ، تم بناء منظومة تفريغ القوس الانزلاقي المستقر مغناطيسيًا (MSGAD) لإنتاج بلازما غير حرارية باستخدام غاز الاركون تحت الضغط الجوي. يستخدم المجال المغناطيسي لتثبيت تفريغ البلازما المنزلق لأغراض الدراسة الخاضعة للسيطرة. تم تسجيل أطياف انبعاث البلازما المتولدة باستخدام منظومة تفريغ القوس الانزلاقي تحت الضغط الجوي ، عند قيمة ثابتة لمصدر الجهد المتناوب (4 كيلو فولت) ومعدلات تدفق مختلفة من 0.5 إلى 2.5 لتر / دقيقة. تم حساب معلمات البلازما مثل درجة حرارة الإلكترون ،كثافة الالكترون ،وتردد البلازما، وطول ديباي .تم استخدام مخطط بولتزمان لحساب درجة حرارة الإلكترون بينما تم حساب كثافة الإلكترون بطريقة توسيع ستارك.أظهرت النتائج أن زيادة معدل تدفق غاز الأرجون من 0.5 إلى 2.5 لتر / دقيقة يؤدي الى زيادة درجة حرارة الإلكترون من 1.138 إلى 1.277 الكترون فولت وكثافة

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الإلكترون من 2.78×10^{17} إلى 3.48×10^{17} سم$^{3-}$. ايضا ، لوحظ زيادة في شدة الخطوط الطيفية عند زيادة معدل تدفق غاز الاركون.

Introduction

Non-thermal plasmas efficiently produce reactive species, like free electrons, free radicals and excited species, which have high electron temperatures and low gas temperatures, thus reducing energy use for gas heating. They are distinguished by various rotational electron temperatures: vibrational and translational. Non-thermal plasmas significantly reduce excessive gas heating, so most of the energy is utilized to create reactive species [1]. This type of plasma is used for numerous applications in chemistry and environment protection [2]. It can be produced at atmospheric pressure using a Gliding Arc Discharge (GAD) [3]

The gliding arc discharge is an auto-oscillating periodic phenomenon that occurs between at least two diverging electrodes positioned in turbulent or laminar gas flow [4, 5]. Gliding arc discharge is a quasi-periodic electrical discharge. It has two distinct phases: the semi-equilibrium phase and the unbalanced phase. The first is a stable discharge caused by the thermal ionization effect, whereas the second is unstable [6].

Gangoli et al. used the Lorentz force concept to create a novel discharge system in which the plasma in the gliding arc is stabilized by a transversal magnetic field. When observed with the naked eye, magnetically stabilized gliding arc discharge (MSGAD) looks like a "plasma disk" as opposed to the standard gliding arc discharge, in which the plasma funnel is displayed with high speed to be a "flame"[7].

Many optical diagnostic tools have been used to investigate gliding arc discharge, including planar laser-induced fluorescence and Optical Emission Spectroscopy (OES) [8]. The OES method is based on observing the light emitted by the plasma gliding arc [9, 10]. In the gliding arc discharge electrons stimulate plasma particles to higher electronic states because of the collisions between the accelerating electrons and the neutral gas atoms. When atoms gain energy, they get excited thus, they move from their ground state to a higher energy level. This process is called excitation. When the electrons are at higher energy levels, they fall back down to the ground state emitting photons of different wavelengths and frequencies, thus of different energies producing different colors of light [11, 12]. In this work, the atmospheric-pressure gliding arc discharge plasma parameters were measured using the optical emission spectrum method

The Boltzmann plot technique, commonly used for spectrum measurements, was used to calculate the relative density of a single line from the same element. However, in order to use the Boltzmann method to calculate electron temperature, the amount of excitement must be determined in accordance with the Local Thermal Equilibrium (LTE) requirement. Under this equilibrium, the conventional Boltzmann plot technique can be applied to determine (T_e) utilizing the following equation [13]:

$$T_e = \frac{-(E_1 - E_2)}{K\,ln(\frac{\lambda_2\, I_2\, g_2\, A_2}{\lambda_1\, I_1\, g_1\, A_1})} \qquad \text{………} \ (1)$$

Where: I_{ji} is intensity, λ_{ji} is the wavelength, g_j is a statistical weight and A_{ji} is the transition probability of spontaneous radiation emission from level i to level j, k is Boltzmann constant, N is the state population densities, and E_i is the excitation energy (in eV) [14]. The electron density is defined as the number of free electron per volume. The identical component and subsequent ionization phases of spectral lines are used in the Saha-Boltzmann equation. The Saha- Boltzmann formula is as follows: [15]

$$n_e = \frac{I_1}{I_2^*} 6.04 \times 10^{21} (T)^{\frac{3}{2}} e^{\frac{E_1 - E_2 - X_Z}{KT}} \qquad \ldots\ldots (2)$$

Where

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

A_2 is the probability of the transition from level 2 to level 1, g_2 is the statistical transition weight from level 2 to level 1, x_z is the energy of ionization (in electron volt), λ_2 is the equivalent transition wavelength between level 2 and level 1.

Debye length is determined using the following equation [16]:

$$\lambda_D = \sqrt{\frac{\epsilon_\circ K_\beta T_e}{n_e e^2}} = 7430 \times \sqrt{\frac{T_e}{n_e}} \qquad \ldots.. (3)$$

Debye length must be as short as possible compared to the system dimensions (L). This initial condition of plasma production is defined as [17]:

$\lambda_D <<< L$

Where L length of plasma. It based on the following equation, plasma frequency can be determined [18]:

$$f_p = 8.98 \sqrt{n_e} \quad (\mathrm{H_z}) \qquad \ldots\ldots (4)$$

One of the fundamental characteristics of plasma is its frequency, which simply depends on density. Due to the low electron mass, plasma frequency is often very high [18].

Experimental Setup

In this experiment, the gliding arc discharge (GAD) system was composed of five essential parts. The gliding arc discharge is an auto-oscillating periodic phenomenon that occurs between at least two diverging electrodes positioned in turbulent or laminar gas flow.

1- Argon gas: to produce plasma in the gliding arc.

2- Gas flow meter (K Weld Corporation, India): was used to measure the amount of gas entering the hollow metal tube. The gas flow rates used in this work were 0.5, 1, 1.5, 2, 2.5 L/min.

3- Magnetic coil of 460 turns to rotate and confine the plasma, and two electrodes, one a high-voltage electrode, which is the central spiral wire, while the other is the container wall which is the grounded electrode.

4- A.C. Power supply (Al-Manara Co., local): This was used to ensure that the electrodes are switched continuously to prevent damage due to high temperature. The power supply supplies a high voltage of 20 kV of frequency in the range of 0 to 150 kHz.

5- D.C. Power supply (Pro'sKit, China): which is connected to the poles of the magnetic coil، this is to supply the coil with electric current to obtain an electromagnet.

The schematic diagram of the gliding arc discharge with a magnetic stabilization system is shown in Figure (1). Figure (2) shows a photograph of the Magnetic Stabilized Gliding Arc Discharge (MSGAD) system. The gliding arc was generated using an A.C. power supply of 4 kV and 9.1 kHz.

The emission spectra were recorded by an optical fiber attached to a UV-NIR spectrometer (S3000- Surwit). The optical emission lines of the Ar spectrum were measured using the National Institute of Standards and Technology (NIST) [19]

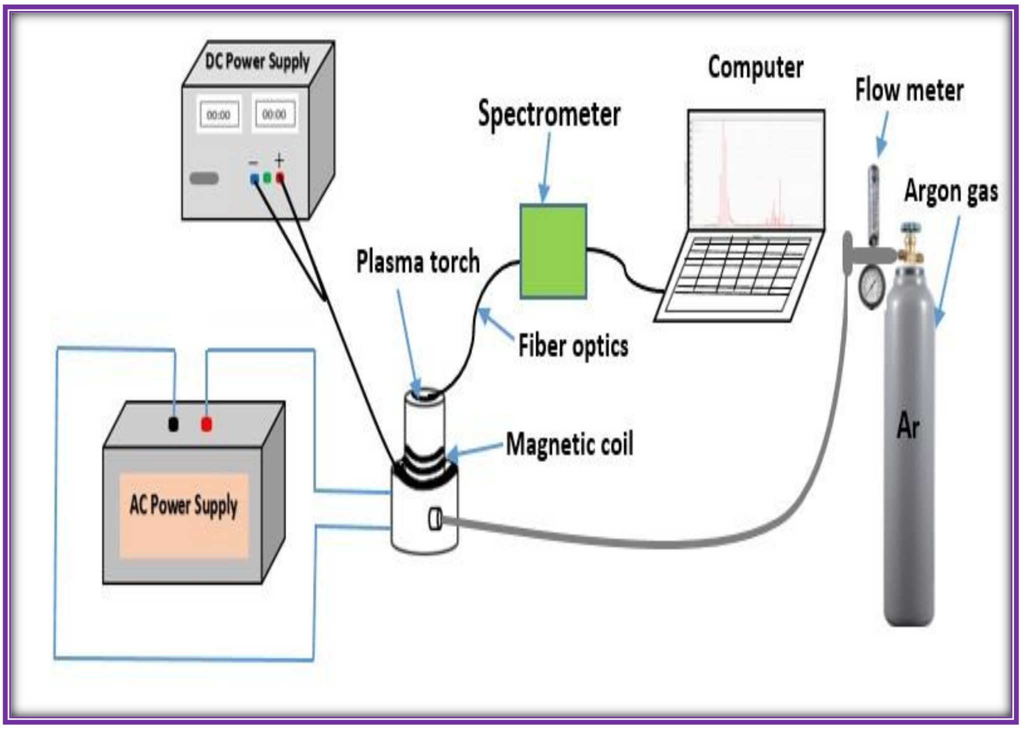

Figure 1: Schematic diagram of the gliding arc discharge (GAD) system

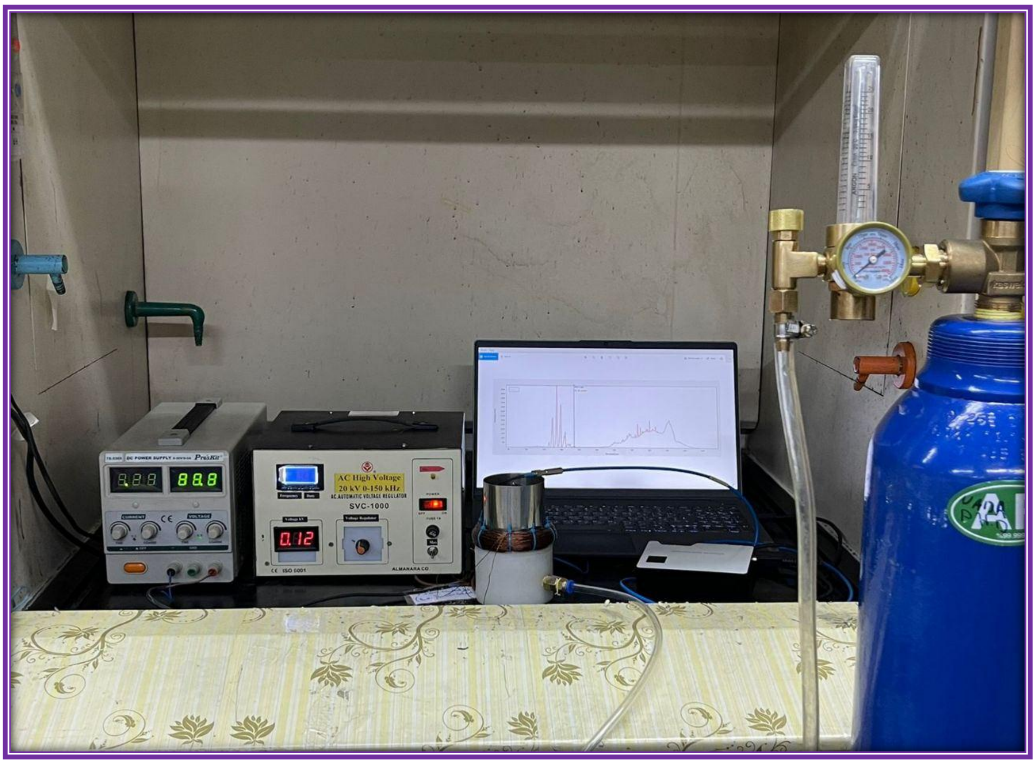

Figure 2: A photograph of the magnetic stabilized gliding arc discharge (MSGAD) system.

Results and discussion

The intensity of the plasma emission spectrum lines gives information about the species concentration in the plasma, making spectroscopy a powerful diagnostic technique for determining the parameters of Ar plasmas. The gliding arc discharge (GAD) device generated the plasma under atmospheric pressure at different argon gas flow rates. Using the OES method, the spectra of argon gas's optical emission at the different gas flow rates were recorded. The spectrum shows many light intensity peaks corresponding to the ions of Ar and many characteristic spectra lines of other atoms versus their wavelengths.

Figure 3 displays the emission spectra of argon gas at flow rates of 0.5 - 2.5 L/min used to produce cold plasma showing distinct standard lines for ArI and ArII at a fundamental wavelength of 600–900 nm [20]. The figure shows that the argon gas flow rate has a significant impact on the emission line intensities. As more molecules travel through the tube at a rising gas flow rate, the intensity of the spectral lines increases. Increasing the amount of gas pushed into the plasma chamber increases the number of excited atoms, thus increasing the intensity of the spectral lines.

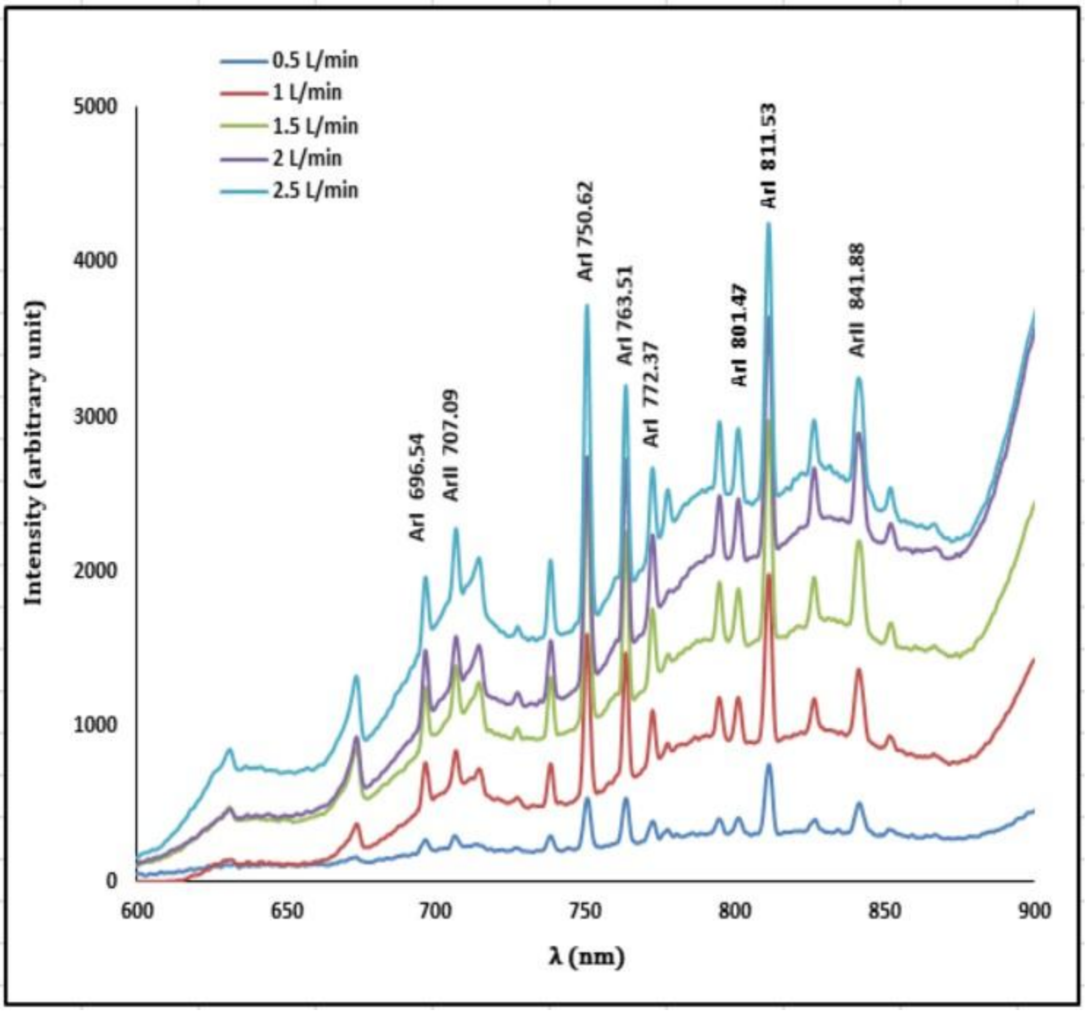

Figure 3: Argon gas optical emission spectra at different gas flow rates (0.5, 1, 1.5, 2, 2.5) L/min

The lines at 696.73, 763.51, 772.37, 801.47, and 811.53 nm were selected to calculate the electron temperature. Figure (4) displays the argon plasma Boltzmann plots for the various gas flow rates. The temperature of an electron is equivalent to the reverse of the fitting line slope. R^2 is a statistics coefficient that ranges from 0 to 1 and expresses the importance of the linear fit; the best R^2 values are those nearer to 1.

The Lorentzian fitting of the ArI line and the change in FWHM broadening at various flow rates are shown in Figure (5).

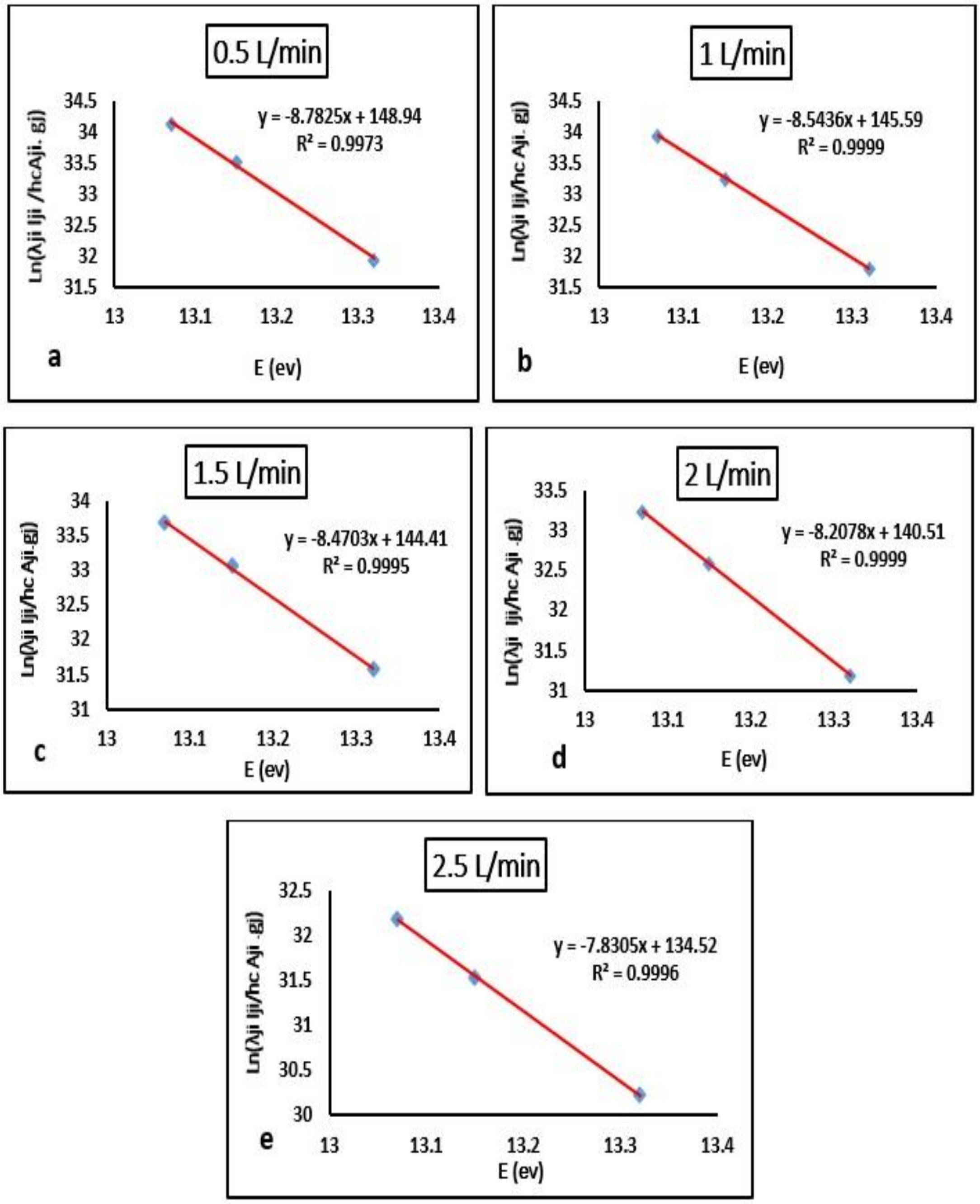

Figure 4: The Boltzmann plot of argon plasma at various flow rates (a) 0.5 L/min, (b) 1 L/min, (c) 1.5 L/min, (d) 2L/min, (e) 2.5 L/min

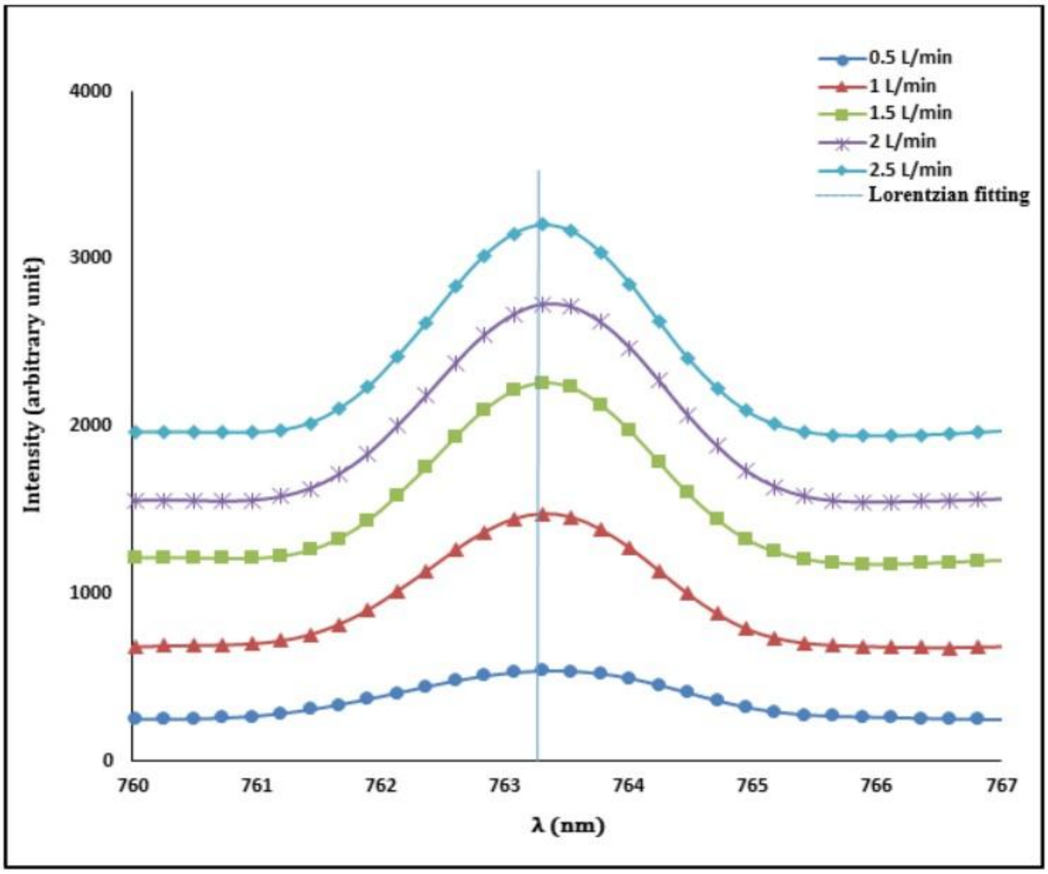

Figure 5: The Lorentzian fitting and Stark broadening for argon discharge from 760 to 767nm.

Equation (1) was used to calculate the electron temperature (T_e) from the line strength ratio. The values for the important parameters were collected from the NIST database and applied to the spectra from the OES [21]. The electron density was calculated using Saha-Boltzmann formula (Equation (2)).

Figure (6) shows the effect of the gas flow rate on the electron temperature (T_e), while Figure (7) demonstrates how the electron density is affected by the gas flow rate (n_e). The graphs clearly show that,T_e and n_e gradually increase with increasing the gas flow rate in the gliding arc discharge system. From the figures and Table 1, a slight increase in electron temperature can be observed as a result of exposure to a high potential difference between the two electrodes, as well as an apparent increase in the electron density. This can be explained by the fact that an increase in the gas flow rate means an increase in the number of gas atoms being pushed into the plasma space, and thus the free path rate of the electrons decreases. In other words, an increase in the number of ionization processes occurred as a result of the increased collisions between accelerated electrons and atoms. The electron temperature and density at 0.5 L/min gas flow rate were determined to be 1.138 eV and 2.78×10^{17} cm^{-3}, respectively; whereas at 2.5 L/min, the values were 1.277eV and $3.48x10^{17}$ cm^{-3}, respectively.

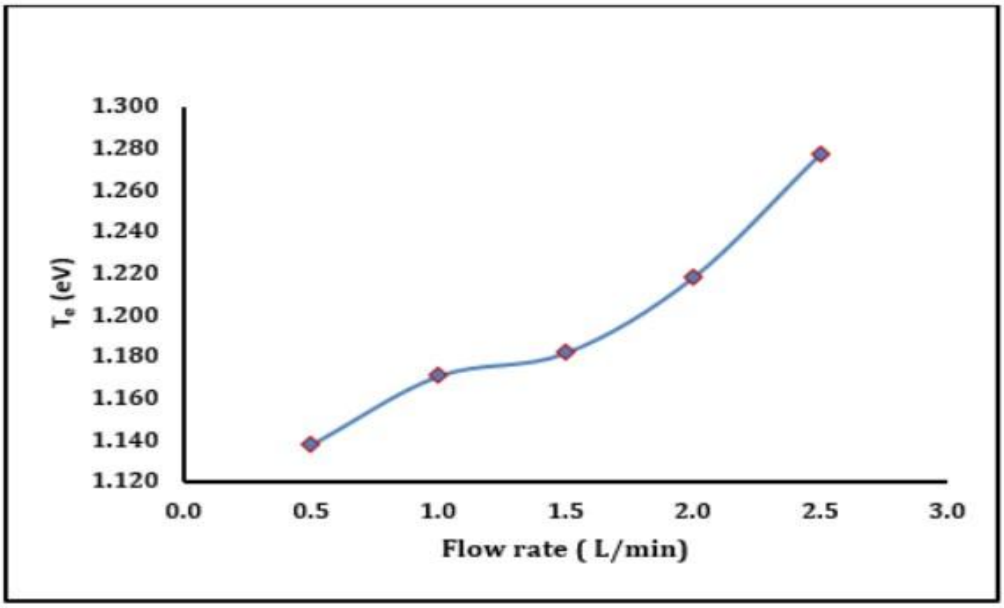

Figure 6: Electron temperature as a function of the gas flow rate.

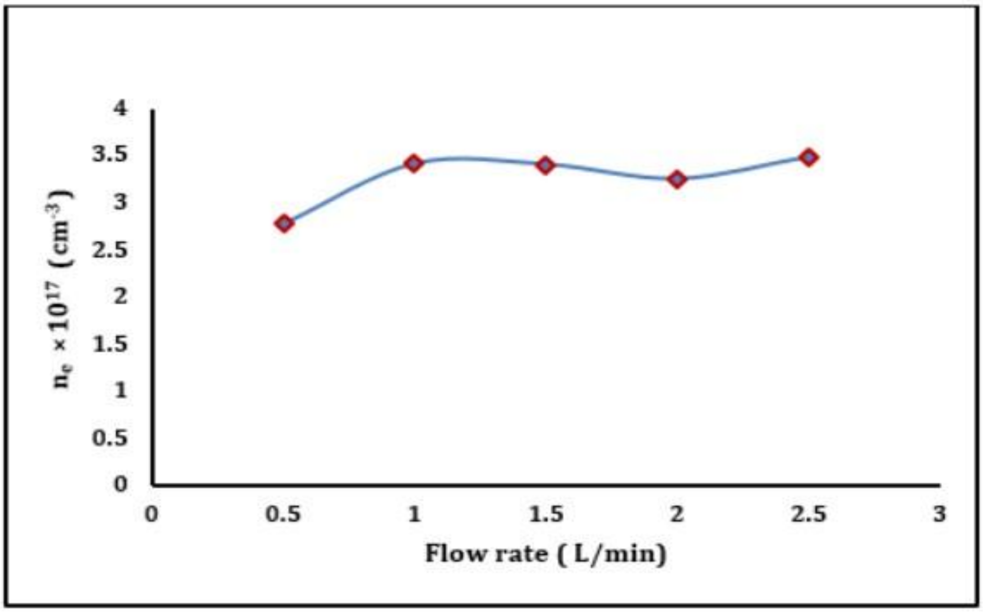

Figure 7: The relationship between electron density and gas flow rate.

T_e, n_e, f_p and λ_D for tornado argon plasma at different gas flow rates are shown in Table 1. The result of the plasma parameters (T_e, n_e), which increased with rising flow rate, allowed for the achievement of criteria plasma.

Table 1: The plasma characteristics for Ar gas at the different flow rates (L/min)

Flow rate (L/min)	T_e (eV)	$n_{e*}10^{17}$ (cm^{-3})	f_p (Hz) $*10^{12}$	λ_D $*10^{-5}$(cm)
0.5	1.138	2.78	14.983	0.150
1	1.171	3.41	16.571	0.137
1.5	1.182	3.40	16.555	0.138
2	1.218	3.25	16.189	0.144
2.5	1.277	3.48	16.564	0.149

4. Conclusion

It has been found that the environment has an important effect on the strength of the cold plasma emission spectrum lines created by a gliding arc discharge. The study demonstrated that an increase in argon gas flow leads to a rise in emission intensity, which implies an increase in gas molecule numbers. This shows that most gas molecules moving through the plasma zone are ionized because the energy provided to the particles by the electric field is suitable for producing secondary ionization of the molecules. Therefore, the peaks were with low intensity at the argon gas flow rate of 0.5 L/min; the intensity increased with the increase of the gas flow rate. The highest intensity was noted at the gas flow rate of 2.5 L/min. This is due to the increase in the number of atoms and molecules pushed to the high voltage area between the electrodes, and thus the increase in the number of excited and ionized atoms, i.e. the increase in the number of gas atoms transformed into the plasma state. These results indicate that the plasma properties represented by electron temperature, Debye length, electron density and plasma frequency are considerably impacted by a rise in the gas flow rate. Therefore, the plasma properties can be changed by changing the gas flow rate.

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Reference

[1] D. Staack, B. Farouk, A. F. Gutsol, and A. A. Fridman, “Spectroscopic studies and rotational and vibrational temperature measurements of atmospheric pressure normal glow plasma discharges in air,” Plasma Sources Sci. Technol, vol.15, no.4, pp. 818–827, 2006.

[2] T. A. Hameed, and S. J. Kadhem, “Plasma diagnostic of gliding arc discharge at atmospheric pressure”. Iraqi Journal of Science, vol.60, no.12, pp.2649-2655, 2019.

[3] J. Zhu, J. Gao, A. Ehn, M. Aldén, A., Larsson, Y., Kusano, and Z. Li, “Spatiotemporally resolved characteristics of a gliding arc discharge in a turbulent air flow at atmospheric pressure,” Physics of Plasmas, vol.24, no.1, pp.013514, 2017.

[4] S. Kolev, and A. Bogaerts, “A 2D model for a gliding arc discharge,” Plasma Sources Science and Technology, vol. 24, no.1, pp.015025, 2014.

[5] Y. D. Korolev, O. B. Frants, V. G. Geyman, N.V. Landl, and V.S.Kasyanov, “Low-current “gliding arc” in an air flow,” IEEE Transactions on Plasma Science, vol.39, no.12, pp.3319-3325, 2011.

[6] J. P. Trelles, “Nonequilibrium phenomena in (quasi-) thermal plasma flows,”Plasma Chemistry and Plasma Processing, vol.40, no. 3, pp.727-748, 2020.

[7] S. P. Gangoli, A. F. Gutsol, and A.A. Fridman, “A Non-equilibrium plasma source: magnetically stabilized gliding arc discharge: I. Design and diagnostics,” IOP Publishing Plasma Sources Science and Technology, vol.19, no.1, pp.065003 2010.

[8] K. A. Aadim, S. N. Mazhir, N. K. Abdalameer, and A. H. Ali, "Influence of Gas Flow Rate on Plasma Parameters Produced by a Plasma Jet and its Spectroscopic Diagnosis Using the OES Technique". IOP Conference Series: Materials Science and Engineering. Vol. 987. No. 1, pp.012020, IOP Publishing, 2020.

[9] Z. W. Sun, J. J. Zhu, Z. S. Li, M. Alden, F. Leipold, M. Salewski and Y. Kusano, “Optical diagnostics of a gliding arc” Opt Express vol. 21, no. 5, pp. 6028- 6044 , 2013.

[10] C. Kong, J. Gao, J. Zhu, A. Ehn, M. Aldén, and Z. Li, “Effect of turbulent flow on an atmospheri cpressure AC powered gliding arc discharge”. Journal of Applied Physics, vol.123, no. 22, pp. 223302, 2018. https://doi.org/10.1063/1.5026703

[11] S. S. Harilal, B. O’Shay, M. S. Tillack, and M. V. Mathew, “Spectroscopic characterization of laser-induced tin plasma”. Journal of applied physics, vol. 98, no. 1, pp. 013306, 2005.

[12] W. S. Hussein, A. F. Ahmed and K. A. Aadim, “Influence of Laser Energy and Annealing on Structural and Optical Properties of CdS Films Prepared by Laser Induced Plasma”. Iraqi Journal of Science, vol. 61, no. 6, pp. 1307-1312, 2020.

[13] H. H. Ley, “Analytical methods in plasma diagnostic by optical emission spectroscopy: A tutorial review”. Journal of Science and Technology, vol.6, no.1, pp.49-66, 2014.

[14] Sh. S. Mahdi, K. A. Aadim, M. A. Khalaf, “New Spectral Range Generations from Laser-plasma Interaction”. Baghdad Science Journal, vol.18, no.4, pp.1328-1337, 2021.

[15] T. S. Hussein, A. F. Ahmed, K. A. Aadim. “Spectroscopic Analysis of CdO: Fe Plasma Generated by Nd: YAG Laser”. Iraqi Journal of Science, Vol. 63, No. 2, pp. 548-555, 2022. 24996/ijs.2022.63.2.12.

[16] S.Chandra Textbook of plasma physics, 1ed. CBS Publishers & Distributors Pvt Ltd, India, 2010.

[17] D. O.Connell, L.J. Cox ,W.B. Hyland , S.J. McMahon , S. Rreuter , W.G. Graham and T. J. Gans ,“Cold atmospheric pressure plasma jet interactions with plasmid DNA” Applied Physics letters. Vol. 98, no.1, pp. 043701, 2011. doi:10.10631/1.3521502.

[18] A. S. AlAamer and A. M. ElSherbini, “Measurement of Plasma Parameters in Laser-Induced Breakdown Spectroscopy Using Si-Lines” World Journal of Nano Science and Engineering. vol. 2, no. 4, pp. 206-212, 2012.

[19] A. P. Rao, M. Gragston, A. K. Patnaik, P. S. Hsu, and M. B. Shattan, “Measurement of electron density and temperature from laser-induced nitrogen plasma at elevated pressure (1–6 bar),” Optics Express, vol. 27, no. 23, pp. 33779-33788, 2019, doi: 10.1364/oe.27.033779.

[20] S. N. Mazhir, N. A. Abdullah, A. F. Rauuf , A. H. Ali and H. Al-Ahmed, “Effects of Gas Flow on Spectral Properties of Plasma Jet Induced by Microwave,” Baghdad Science Journal Vol. 15 no. 1 pp. 81-86, 2018. http://dx.doi.org/10.21123/bsj.2018.15.1.0081.

[21] National Institute of Standards and Technology (NIST) atomic spectra database, (version 5), 2015. Available at http://www.nist.gov/pml/data/asd.cfm, last updated: November 2.