Volume 16, Number 3, 2023. pp. 321-327

Jordan Journal of Physics

ARTICLE

Effect of Working Gas and Applied Voltage on the Estimation of Power and Electron Density in Gliding Arc Discharge (GAD) System

Santosh Dhungana[a,b], **Rajesh P. Guragain**[a], **Hom B. Baniya**[c], **Ganesh K. Chettri**[a], **Gobinda P. Panta**[a] and **Deepak P. Subedi**[a]

[a] *Department of Physics, School of Science, Kathmandu University, Dhulikhel, Nepal.*
[b] *Central Department of Physics, Kirtipur, Kathmandu, Nepal.*
[c] *Department of Physics, Amrit Campus, Kathmandu, Nepal.*

Doi: https://doi.org/10.47011/16.3.7

Received on: 29/09/2021; *Accepted on: 28/12/2021*

Abstract: Atmospheric pressure gliding arc plasma is generated by a 50 Hz (0-13 kV) AC power supply. The electrical properties of the produced plasma are investigated with the help of an oscilloscope. In this work, the relationship between applied voltage, breakdown voltage, and discharge current is studied for air, argon, oxygen, and nitrogen gases. Similarly, the effect of the nature of gases on breakdown voltage and discharge current is studied. The power consumed by the discharge for different gases is obtained by current-voltage characteristics. It is found that among air, nitrogen, argon, and oxygen, argon consumes minimum and nitrogen consumes maximum power. Specifically, at the maximum applied voltage of 10.2 kV, oxygen and nitrogen consume approximately 56-57% more power than argon. Electron density, one of the most essential plasma parameters, is evaluated and compared using an electrical approach for several fading gases. The electron density is found to be increasing with the increase in applied voltage, and the value of electron density is found to be larger in argon discharge.

Keywords: Gliding arc discharge, I–V characteristics, Power consumption, Discharge voltage, Electron density.

Introduction

Thermal plasma and non-thermal plasma are the two most common forms of electrically generated plasma. Thermal plasma is typically hot and has the same ion and electron temperature in contrast non-thermal plasma has much higher average electron energies in comparison to gas molecules and therefore is more chemically selective [1]. Thanks to its chemical selectivity, non-thermal plasma has found applications in various fields, including material processing [2, 3], combustion enhancement [4], gas conversion [5], sterilization [6], etc. Moreover, recent success in the application of non-thermal plasmas in medicine, agriculture, and food technologies now opens up possibilities in areas where plasma technologies were previously unavailable [7]. Non-thermal plasma has been generated using a variety of techniques, including corona discharge [8], dielectric barrier discharge (DBD), microplasmas, plasma jets, and GAD [9]. Among these discharge systems, gliding arc discharge is becoming increasingly popular among researchers for several reasons. It can operate at and domestic frequencies in atmospheric pressure conditions, does not require specific barrier material, and can provide high operating power under non-thermal conditions.

Corresponding Author: Santosh Dhungana **Email**: sanein1@yahoo.com

Czernichowski in 1988 offered the two-dimensional gliding arc facility as a novel solution to gaseous pollution emission control and treatment for the first time [10]. Later, Fridman conducted a lot of pioneering work with his coworkers at Drexel University [1]. Their findings suggest that GAD is an auto oscillating discharge that starts between the electrodes of divergent geometry, through the force of the laminar or turbulent flow of gas or air. In this discharge system, a breakdown of atmospheric gas is generated at the shortest gap between two divergent electrodes. Following the breakdown, the plasma continues to move in the same direction as the gas flow. This leads to an increase in applied voltage and a transition from thermal to non-thermal equilibrium, which continues until the applied voltage reaches the critical voltage required for the next breakdown [11]. Plasma generated by the gliding discharge has thermal or non-thermal properties depending on the system parameters, such as power input and flow rate [12].

The gliding arc discharge is a simple and low-cost method of producing non-thermal plasma. It has a dual character of thermal and non-thermal plasma and can involve relatively high electric powers compared with the corona discharge [13]. Most of the recent applications are focused on gas conversion and decontamination processes [14, 15, 16]. Due to their strong oxidizing properties, humid air gliding arc discharge and gliding arc to a water surface have been employed recently for the degradation of organic waste solution or organic pollutants in water [17, 18]. Similarly, many researchers reported that plasma-activated water (PAW) generated from GAD can enhance the germination and growth rate of the plants [19, 20] and can be used for sterilization of medical devices [21].

The chemical composition of the working gas has a great influence on the operation of the reactor and the parameters of the generated plasma [22]. In order to widen the application of the gliding arc discharge, it is necessary to understand the electrical characteristics of the GAD system and the role of working gas in the discharge process and power consumption [23]. In addition to obtaining specific gas species, the choice of gases should be made with the aim of minimizing power consumption in the discharge. In this paper, the electrical method is used to estimate the electron density, which is an important diagnostic tool for the classification of plasma. Similarly, the determination of electron density is crucial for the selection of plasma applications in various fields, such as material processing, agriculture, food preservation, etc. [24]. The resistance of the inter-electrode gap depends on the kind of gas and its flow rate [25], so the role of working gases on discharge voltage and discharge current as well as on consumption of power per cycle is also investigated.

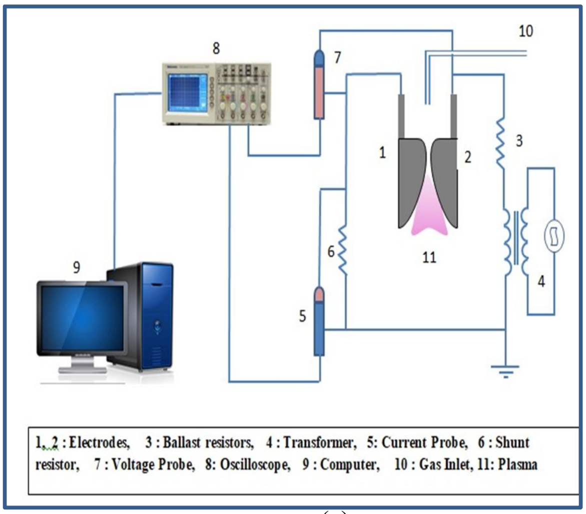
Materials and Methods

The diagrammatical representation of the experimental setup for generating the discharge is shown in Fig. 1. This setup features a polycarbonate box measuring 15×15×15 cm. Two diverging aluminum electrodes are attached to the polycarbonate box keeping the minimum distance of 3 mm. To allow the appropriate gas to enter, a small hole is drilled into the upper face of the chamber. The flow rate for all gases is kept constant at 5 L/min with the help of an analog gas flow meter. High voltages (0-13 kV) and a line frequency of 50 Hz are supplied through a 1.7 MΩ ballast resistor to produce the discharge. The voltage dropped on the electrodes is measured using a high-voltage probe (PINTEK HVP-28HF), while the current flowing in the circuit is measured with a current probe. The measurement and analysis of the current and voltage waveform are done by an oscilloscope (TEKTRONIX TDS 2002, 60 MHz).

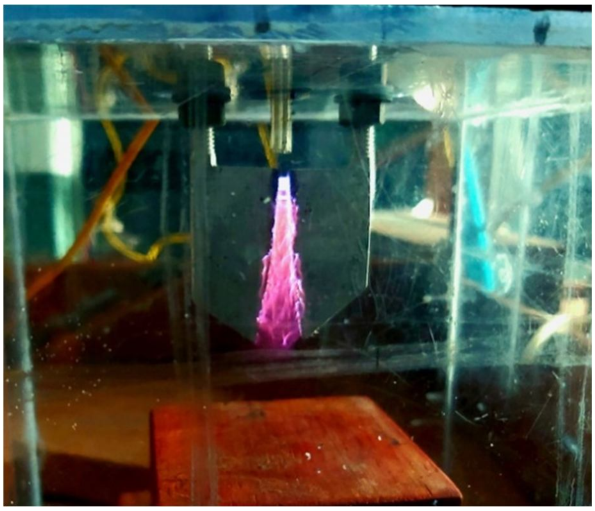
Results and Discussion

I–V Characteristics

The current-voltage (I-V) waveforms for air, argon, nitrogen, and oxygen at the flow rate of 5L/min are shown in Fig. 2. In each cycle and for every gas, the current waveforms exhibit a sinusoidal nature, while the voltage waveforms appear as sawtooth patterns. The shape of the voltage curve is attributed to the formation of four types of peaks in positive as well as negative cycles [26, 27]. Type A occurs at the shortest electrode gap, just as the arc ignites. At this point, the gas breaks down, and the resistance is near zero, with most of the power source's voltage being used to initiate the arc. With the continuous flow of gas, the power supplied can no longer compensate for the energy used for arc growth, and the arc begins to fade. This causes an increase in voltage at first, followed by a reduction in voltage, and the process repeats itself, forming B- and C-type peaks as illustrated in Fig2(b). As the power supply reverses after a specified period of time, the voltage changes abruptly, and D type peaks occur. These types of peaks can be seen in negative as well as positive cycles of discharge voltage in all four working gases.

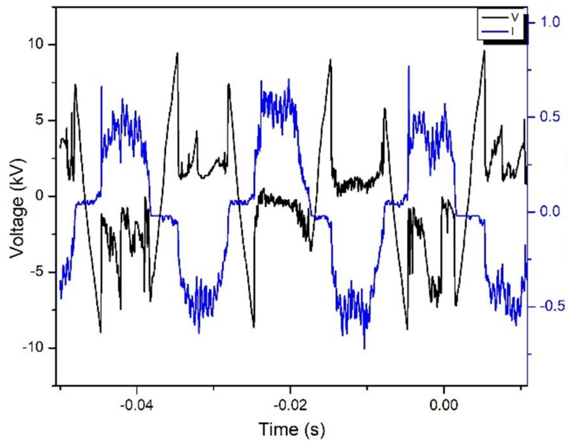


(a)

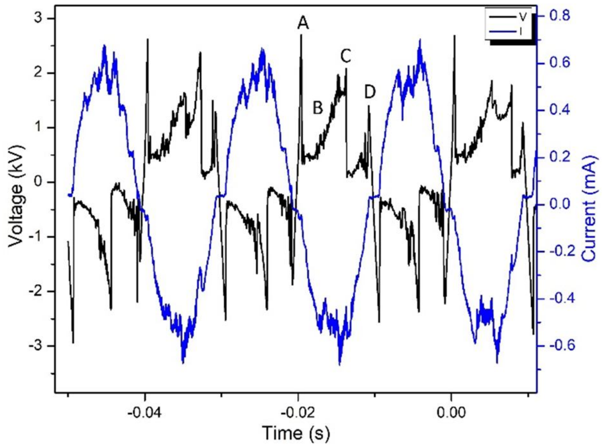


(b)

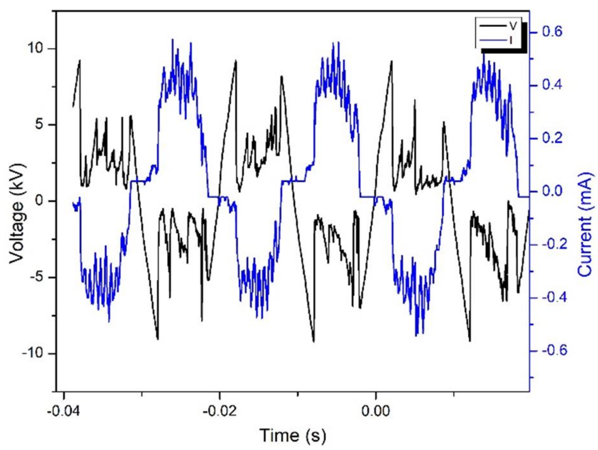
FIG.1. (a) Schematic diagram of the experimental arrangement of the GAD system. (b) Photograph of discharge.



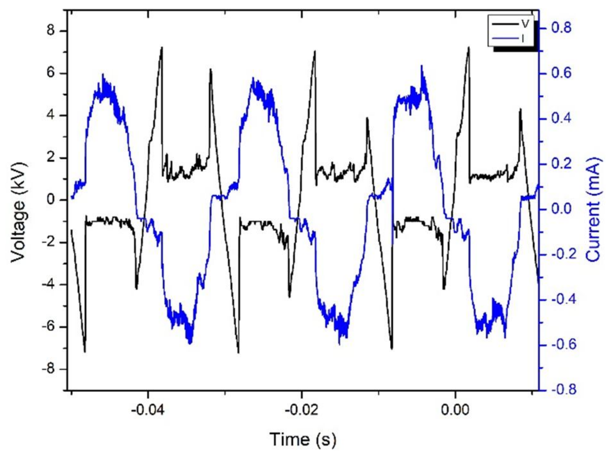
(a) Air



(b) Argon



(c) Nitrogen

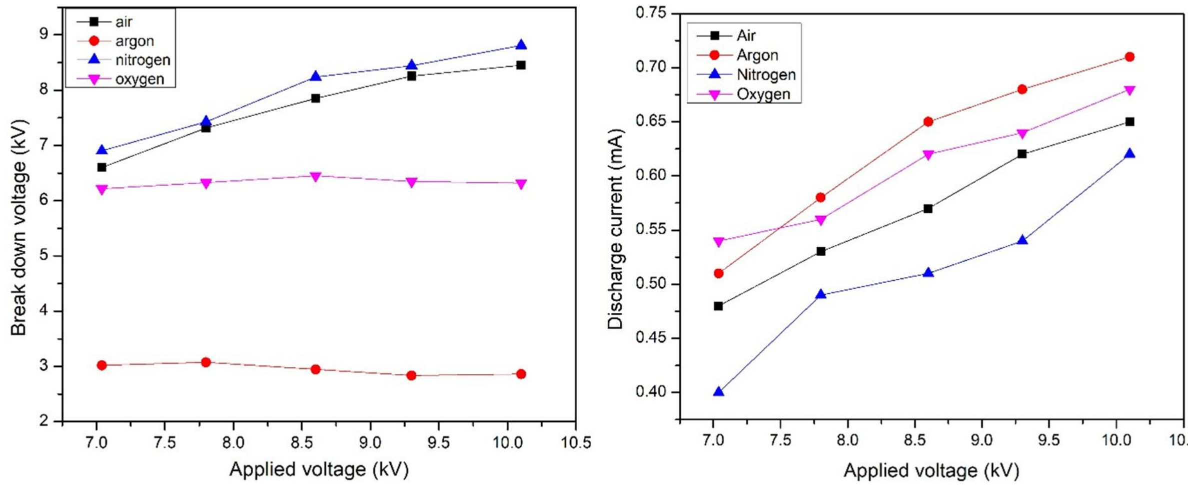


(d) Oxygen

FIG. 2. Variation of I-V curve with respect to time in (a) air, (b) argon, (c) nitrogen, and (d) oxygen discharge.

The current wave structure is nearly identical in all gases, although the peak value varies for different fading gases. More filamentary peaks are seen in air and nitrogen and less filamentary peaks are seen in the case of argon. The effect of applied voltages (voltages given to the power supply) on the breakdown voltages (average peak value of voltage) of various working gases is shown in Fig. 3(a). It depicts that in the case of nitrogen, air, and argon, the applied voltage has a minor effect on the breakdown voltage, but not in the case of oxygen. If we observe the dependence of breakdown voltage on working gases, argon has the least breakdown voltage and nitrogen has the most. The breakdown voltage of the oxygen is two times greater than that of argon in all applied voltages.

Fig. 3(b) shows the relationship between applied voltage and discharge current (average peak value of current) for various gases which illustrates that discharge currents rise linearly with applied voltages in all fading gases. Fig. 3(b) also shows that when nitrogen gas is faded, there is the least current in the discharge. In contrast, argon, with its low breakdown voltage, quickly ionizes, generating electrons and ions from neutral atoms or molecules. These charged particles migrate to the anode and cathode, respectively, resulting in higher currents compared to other gases [28].



(a) (b)

FIG. 3. Variation of (a) discharge voltage and (b) discharge current with applied voltage.

Estimation of Power Dissipated

The power dissipated in the discharge can be calculated by integrating the arc voltage and current, as given in the equation:

$$\boldsymbol{Power\ (P)} = \frac{1}{T}\int_0^{t=T} i(t)\, v(t) dt \qquad (1)$$

Here, *i(t)* and *v(t)* are the current and voltage developed during the discharge [29].

Fig. 4 illustrates the relation between powers dissipated with applied voltage for different gases. The graph depicts that power has somehow linearly depended on the applied voltage. In all gases, the power dissipated during the discharge increases as the applied voltage increases. The type of gas has a significant impact on power dissipation, as seen in the diagram. Argon exhibits the lowest power consumption (0.9 to 1.75 watts), while nitrogen displays the highest consumption (1.6 to 2.8 watts) during the discharge. Meanwhile, power consumption for oxygen and air discharge falls between the values observed for nitrogen and argon, as indicated in the figure. At maximum applied voltage the power consumption in the case of nitrogen and oxygen is 56-57% greater than that of argon. The order of estimated value of powers for all four gases agrees with the previous work done by Guragain *et al.* [30]. As argon has the least breakdown voltage and least discharge voltage among all other gases and has no significantly larger value of the discharge current, it consumes the least power. On the other hand, nitrogen, which possesses a higher triple bond energy (941.69 kJ mol^{-1}) [25], requires a higher peak voltage and, subsequently, a higher average discharge voltage, resulting in greater power consumption.

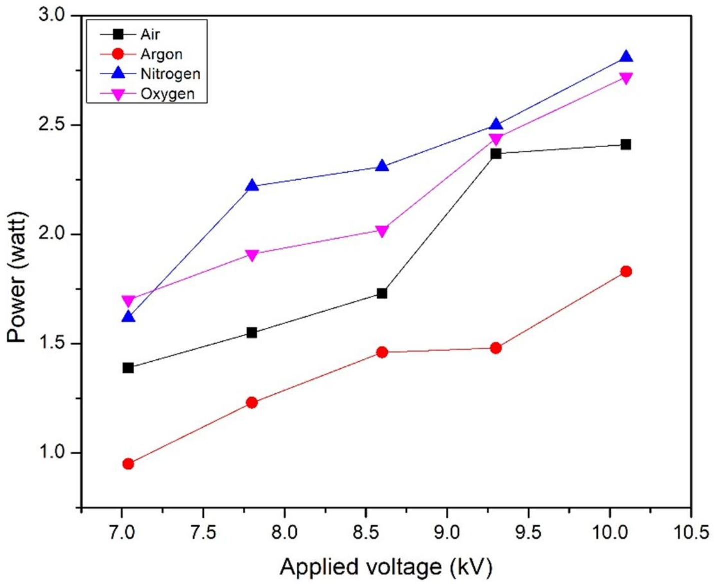


FIG. 4. Power dissipated on the discharge for different working gas.

Estimation of Electron Density

Estimation of electron density is an important characteristic of plasma which not only gives the information on type and nature of the plasma but also provides knowledge on its potential applications. There are various ways to calculate the electron density using electrical and optical methods. Here, the electron density of the discharge is calculated using the electrical method or using current density method. In this method, the electron density is obtained by

$$\boldsymbol{n_e} = \frac{j}{eE\mu} \quad (2)$$

where j is current density, e is the electronic charge of electron, E is the electric field, and $\boldsymbol{\mu}$ is electron mobility [31].

The current density is calculated by dividing the average discharge current by the area of the discharge channel, i.e. $\boldsymbol{j} = \frac{I_{av}}{A}$. The average area of the discharge channel is determined by multiplying the average area of a single channel by the total number of filaments. The average diameter of a single channel is taken as 0.02 cm from Kogelschatz [32] and the total number of filaments is counted with the help of the peak analyzer of origin. The electric field is calculated by dividing the discharge voltage (average voltage) by the minimum gap between the electrodes. The electron mobility of all gases is estimated by using BOLSIG+ [33].

Fig. 5 shows the relation between applied voltage and electron densities for air, argon, nitrogen, and oxygen. In all gases, the electron density is found to be in the order of 10^9 cm^{-3} which is similar to the previous result by Kim *et al.* [34]. Electron density was found to increase slightly with the applied voltage in air, nitrogen, and oxygen, but in the case of argon the electron density increases significantly with applied voltage. The most important fact that can be concluded from the diagram is the dependence of electron density on the nature of the gas. The figure demonstrates that the discharge using argon as the working gas has the highest electron density, while the discharge using nitrogen has the lowest electron density. Air and oxygen as working gases have slightly greater electron densities than nitrogen. This can be ascribed to the fact that argon has greater current density and a lesser electric field than that of other gases.

Conclusions

The electrical properties of the gliding arc generated at atmospheric pressure plasma are investigated with the help of an oscilloscope. In this study, we investigate the relationship between applied voltage, breakdown voltage, and discharge current for air, argon, oxygen, and nitrogen gases. It is found that breakdown voltages for all gases linearly depend on applied voltages and discharge current slightly increases with an increase in applied voltages for air, oxygen, and nitrogen but slightly decreases in the case of argon. Additionally, when considering the nature of gases, it is evident that among air, nitrogen, argon, and oxygen, argon consumes the least power (0.9 to 1.75 watts), while nitrogen consumes the highest power (1.6

to 2.8 watts). Electron density, one of the most essential plasma parameters, is evaluated and compared using an electrical approach for several fading gases. For all gases, the electron density of the discharge is determined to be on the order of 10^9 cm^{-3}. The value of electron density rises as the applied voltage increases, and it is notably higher in argon discharge compared to the other gases.

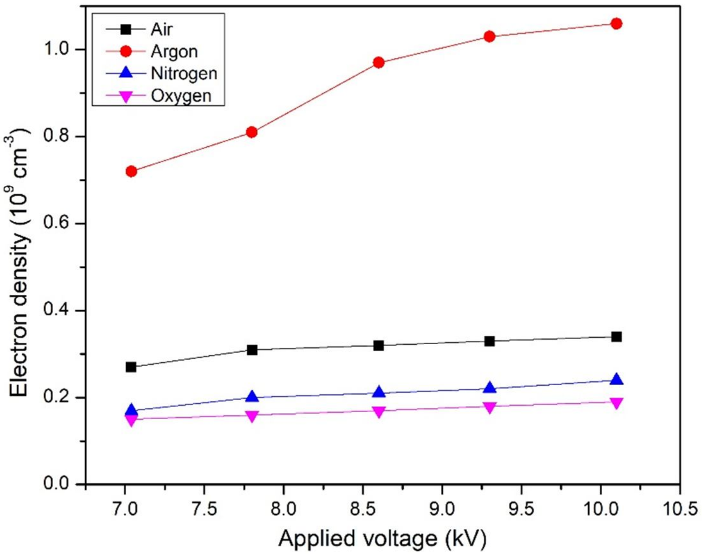


FIG. 5. Electron density of the discharge for different working gases.

Acknowledgments

The corresponding author would like to express his gratitude to the University Grants Commission (UGC) of Nepal for providing financial support under award no. M.Phil 75/76-S & T-8.

References

[1] Kong, C., Gao, J., Zhu, J., Ehn, A., Aldén, M., *et al*., Phys. Plasma, 24 (2017) 1.

[2] Borcia, C., Borcia, G., Dumitrascu, N., 28th ICPIG Conf. Proceedings, Prague, (2007) 700.

[3] Castro Vidaurre, E.F., Achete, C.A., Gallo, F., Garcia, D., Simao, R. and Habert, A.C., Mat. Res., 5 (1) (2002) 37.

[4] Ombrello, T., Qin, X., Ju, Y., Gutsol, A., Fridman, A. and Carter, C., AIAA J., 44 (1) (2012) 142.

[5] Bo, Z., Yan, J., Li, X., Chi, Y. and Cen, K., Int. J. Hydrogen Energ., 33 (2008) 5545.

[6] Nguyen, D.V., Ho, P.Q., Pham, T.V., Nguyen, T.V. and Kim, L., Environ. Eng. Res., 24 (2019) 412.

[7] Brandenburg, R., Bogaerts, A., Bongers, W., Fridman, A., Fridman, G., *et al*., Plasma Processes Polym., e1700238 (2018) 1.

[8] Xie, Y., He, H., He, J. and Wu, C., IEEE T. Plasma Sci., 42 (4) (2014) 990.

[9] Weltmann, K.D., Kolb, J.F., Holub, M., Šimek, M., Ostrikov, K., *et al*., Plasma Process Polym. (2019) 16:e1800118.

[10] Bo, Z., Yan, Y., Li, X., Chi, Y. and Cen, K., J. Hazard. Mater., 155 (2007) 494.

[11] Mitsugi, F., Ohshima, T., Kawasaki, H., Kawasaki, T., Aoqui, S., *et al*., IEEE T. Plasma Sci., 42 (2014) 3681.

[12] Mutaf-Yardimci, O., Saveliev, A.V., Fridman, A.A. and Kennedy, L.A., J. Appl. Phys., 87 (2000) 1632.

[13] Du, C.M., Yan, J.H. and Cheron, B.G., Plasma Chem. Plasma P., 27 (2007) 635.

[14] Du, C.M., Yan, J.H., Li, X.D., Cheron, B.G., You, X.F., *et al*., Plasma Chem. Plasma P., 26 (2006) 517.

[15] Nagassou, D., Mohsenian, S., Bhatta, S., Elahi, R. and Trelles, J.P., Sol. Energy, 180 (2018) 678.

[16] Gong, X., Lin, Y., Li, X., Wu, A., Zhang, H., Yan, J. and Du, C., J. Air Waste Manage., 70 (2020) 138.

[17] Doubla, A., Bello, L.B., Fotso, M. and Brisset, J.L., Dyes Pigments, 77 (2008) 118.

[18] Ghezzara, M.R., Saïm, N., Belhachemia, S., Abdelmaleka, F. and Addoua, A., Chem. Eng. Process.: Process Intensification, 72 (2013) 42.

[19] Thirumdas, R., Kothakota, A., Sai-Kiran, K.S., Pandiselvam, R. and Prakash V.U.B., Adv. in Res., 12 (2017) 1.

[20] Sivachandiran, L. and Khacef, A., RSC Adv., 7 (2017) 1822.

[21] Abuzairi, T., Ramadhanty, S., Puspohadiningrum, D.F., Ratnasari, A., Poespawati, N.R., *et al.*, AIP Conf. Proc., 1933 (2018) 1.

[22] Komarzyniec, G. and Aftyka, M., Appl. Sci., 10 (3295) (2020) 1.

[23] Roy, N.C. and Talukder, M.R., Phys. Plasmas, 25 (2018) 1.

[24] Kieft, I.E., Laan E.P. and Stoffels, E., New J. Phys., 6 (2004) 149.

[25] Diatczyk, J., Komarzyniec, G. and Stryczewska, H.D., Int. J. Plasma Environ. Sci. Technol., 5 (1) (2011) 12.

[26] Lu, S.Y., Sun, X.M., Li, X.D., Yan, J.H. and Du, C.M., Phys. Plasmas, 19 (2012) 1.

[27] Tu, X., Yu, L., Yan, J.H., Cen, K.F. and Chéron, B.G., Phys. Plasmas, 16 (2009) 1.

[28] Bogaerts, A., Chen, Z. and Gijbels, R., Surf. Interface Anal., 35 (7) (2003) 593.

[29] Wang, W., Mei, D., Tu, X. and Bogaerts, A., Chem. Eng. J., 330 (2017) 11.

[30] Guragain, R.P., Baniya, H.B., Pradhan, S.P. and Subedi, D.P., AIP Adv., 11 (2021) 1.

[31] El-Zein, A., Talaat, A.M., El-Aragi, G. and El-Amawy, A., IEEE T. Plasma Sci., 44 (2016) 1155.

[32] Kogelschatz, U., IEEE T. Plasma Sci., 30 (2002) 1400.

[33] Hagelaar, G.J.M. and Pitchford, L.C., Plasma Sources Sci. T., 14 (2005) 722.

[34] Kim, J.H., Choi. Y.H. and Hwang, Y.S., Phys. Plasmas, 13 (2006) 1.