Construction and spectral characterization of the gliding arc reverse vortex flow plasma system at atmospheric pressure

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Abstract. In this paper, a low-cost reverse-gliding arc three-dimensional reactor with local materials and a homemade voltage source was proposed. This system works by pumping out argon gas while mixing in atmospheric air. The spectral properties of the resulting arc were investigated, as well as the calculation of electron temperature and density. The process of mixing air with argon gas is a novel method for obtaining nitrogen gas at a low cost and with ease of access. Nitrogen gas has numerous applications, and the findings are promising for future applications.

1. Introduction
Chemical plasma systems are classified into two types: thermal and non-thermal, each with advantages and disadvantages [1]. Thermal plasma systems are capable of delivering high energies and extremely high temperatures, as well as generating excitation without the use of selective excitation [2]. This results in significant cooling requirements and electrode wear issues; as a result, its efficiency is limited and it can only be used with plasma sources. Non-thermal systems provide high selectivity and energy efficiency [3]. These systems provide special cooling, in that they operate at lower temperatures, but operating pressures are typically limited, limiting production rates in large industries [2]. As a result, it became necessary to devise a method that combines both thermal and non-thermal advantages of discharging physics [4]. The gliding arc discharge, which combines the high energies of the reactor with a high degree of imbalance to support selective chemical processes, has piqued the interest of many scientists and engineers [5]. The plasma discharge oscillates between two phases, semi-equilibrium and unbalanced; the quasi-equilibrium phase is related to the thermal ionization effect and is a stable discharge [4, 6]. The cylindrical geometry of the Reverse Vortex Flow Reactor (RVF) is described [5]. These reactors offer excellent thermal insulation for active species (electrons and ions) [7]. This significantly reduces energy loss in the surrounding areas, improving energy efficiency [8]. Previous research developed a reactors to generate gliding arc plasma, but it was costly and difficult to obtain raw materials. Because our system was proposed in this study due to its low cost and availability of raw materials in the local market, the spectral properties of this system were investigated. S. Y. Lu and others studied the electrical properties of the gliding arc plasma of nitrogen, oxygen, and air [9]. Ananthanarasimhan et al. The GA system was developed with a steel disk surrounded by silicon rings and a quartz cylinder [10]. The electrical properties were studied and the shapes of the plasma produced by different gas flows were studied, Sasujit et al. The RVF-GA reactor was developed, investigated electrical properties and produced plasma flame images with different carrier gases [11]. Previous studies did not adopt the property of mixing air with gas to obtain a rotating plasma, as well as studying spectra
for gas pumping alone, as well as studying spectra for all mixing results. Previously developed systems were also very expensive.

2. Materials and methodology

2.1 Mechanical design

A system for producing reverse flow plasma (RVF) at atmospheric pressure at the lowest possible cost has been developed. The system is comprised of an argon gas bottle, an air compressor, a homemade power supply, and a vortex plasma torch production reactor, as shown in Figure 1.

![Figure 1. Depicts a system diagram.](image1)

The reactor was built locally and consists of three regions: the base and cover are made of Teflon, and the middle part (which contains the plasma) is a Pyrex cylinder as shown in Figure 2.

![Figure 2. Depicts a reactor diagram.](image2)
The cover has an opening through which an iron plug, which serves as the first ground pole, passes. On the outside, a DC motor controls the torch's movement up and down to achieve different lengths. The base has four holes tangent to the circle's axis on both sides for pumping gas into the Gliding arc tornado (GAT). Below the tangent holes, there is a hole with a screw for attaching the stable copper disk under the base (which has a hole in the middle of 3 mm for permeability) that is connected to the power supply and serves as the system's second pole (see Figures 3 and 4).

![Figure 3. The base part in the proposed reactor.](image)

![Figure 4. Copper electrode (a) scheme (b) photo.](image)

### 2.2 Types of gases used and their purpose

1. Pumping pure argon gas.
2. Air is mixed with argon gas in a one-to-one ratio.
3. Air is mixed with argon gas in a one-to-half (air) ratio.
4. Air is mixed with argon gas in a one-to-quarter (air) ratio.

The purpose of pumping argon is to power the system and obtain a perfectly rotating torch. To obtain nitrogen gas at the lowest possible cost, in the simplest and most abundant way, atmospheric air was pumped into the reactor. However, the RVF was not obtained because it was mixed with argon gas in various proportions to obtain nitrogen gas. Thus, the achievement of obtaining a rotating arc with a gas mixture and the highest proportion of nitrogen gas, because it is known that atmospheric air is mostly composed of this gas.

### 2.3 Optical emission spectroscopy

The optical emission spectroscopy diode-array type was used in plasma diagnostics because it is fast, lightweight, has no moving parts, and requires little power [13]. Figure 5 optical emission spectroscopy used.
Figure 5. Schematic of the spectrometer used.

The light signal was collected and brought into the instrument (1) via a fiber optic cable, where it was spread into a rainbow of colors using a diffraction grating (2). The scattered light strikes an array of photodiodes (3), each of which responds to only a narrow range of wavelengths impinging on it. A charge coupled device (CCD) is connected to the diodes (4). Photodiodes take advantage of the photovoltaic effect at the interface of a semiconductor and a metal. Electron transitions cause a voltage to be generated in the cell. Each diode's voltage is converted to digital counts and sent to a dedicated computer running spectrum analysis software. The acquired spectrum is displayed on the screen immediately and saved in computer files. A single scan takes a fraction of a second, after which the diodes can be discharged and ready for the next scan.

3. Results and discussions

The vortex forms inside the reactor as a result of gas being pumped at high speeds through the transverse holes to ensure that the gas travels from one hole to the next. As shown earlier in the methodology, the reactor should be cylindrical (i.e. have a diameter). Initially, Argon gas was pumped to ensure reactor operation and to achieve an ideal arc at various flow rates (6, 8, 10, 12, and 14) L/ min. Figure 6 depicts the ideal arc that appeared to us when pure argon gas was pumped.

![Figure 6](image)

Figure 6. The maximum plasma length versus different pure argon gas flow rate (a) at 6 L/min, (b) at 8 L/min, (c) at 10 L/ min (d) at 12 L/min, and (e) at 14 L/min

From Figure 6, the arc length changes in direct proportion to the flow rate. The system was then tested by pumping regular air to obtain nitrogen in a simple and inexpensive manner, but we did not obtain the rotating gliding arc. As a result, air was mixed with argon gas in various proportions, and the spectral effects of all results were investigated. Figures 7-9 are represented plasma obtained by mixing air pumping with argon in one-to-one, half-to-one, and quarter-to-one ratio respectively.
Figure 7. The maximum plasma length from mixing air-argon with proportions one-to-one of versus different flow rate (a) at 10 L/min, (b) at 14 L/min, (c) at 20 L/min (d) at 26 L/min, and (e) at 30 L/min.

Figure 8. The maximum plasma length from mixing air-argon with proportions one-to-half of versus different flow rate (a) at 7 L/min, (b) at 10 L/min, (c) at 15 L/min (d) at 19 L/min, and (e) at 22 L/min.

Figure 9. The maximum plasma length from mixing air-argon with proportions one-to-quarter of versus different flow rate (a) at 7 L/min, (b) at 9 L/min, (c) at 12 L/min (d) at 16 L/min, and (e) at 19 L/min.

We can see from the Figures 7-9 that as the air percentage increases, the arch becomes less bright and more orangey due to the increase in nitrogen content. In terms of length, we notice a difference between the mixing lengths, which are shorter than the lengths when pumping pure argon.

Figure 10 depicts the plasma spectra produced by pumping argon gas alone at various flow rates (6, 8, 10, 12, and 14) L/min. We notice that the spectrum appears between (650-950) nm, which is the argon gas region.
Figure 10. Pure argon gas produced a plasma spectrum with varying flow rates. The spectra in Figure 11 are shown when argon gas is mixed with atmospheric air in a one-to-one ratio, when the air is mixed Flow rates (10, 14, 20, 26, and 30) L/min, we can get nitrogen gas, because it makes up the largest proportion of air, and thus we can get nitrogen oxides at the lowest cost.

Figure 11. Plasma spectrum produced by mixing air-argon with proportions one-to-one with various flows rate. Figure 12 depicts the spectra obtained when argon gas is mixed with air in a one-to-half air-to-argon-gas ratio at flow rates of (8, 11, 15, 19, and 22) L/min.
Figure 12. Plasma spectrum produced by mixing air-argon with proportions one-to-half with various flows rate.

Figure 13 depicts the spectra obtained when argon gas is mixed with atmospheric air in a one-to-quarter air-to-argon ratio at flow rates of (6, 9, 13, 17, and 20) L/min.

Figure 13. Plasma spectrum produced by mixing air-argon with proportions one-to-quarter with various flows rate.

As the percentage of air increases, so does the percentage of nitrogen gas, which is required. RVF cannot be obtained at less than these proportions.

The Boltzmann equation was used to calculate the electron temperature [15], from a better fit linear slope requiring peaks originating from the same atomic species and the same ionization phases. At a flow rate of 6 L/min, the best fitting score was (696.3, 706.5, 763.4, 801.6) nm, 8 L/Min the best
Figure 14. Boltzmann plot to pump argon gas with different flows.
Figure 15. Boltzmann plot to pump air with argon gas in a one-to-one ratio.

Figure 16. Boltzmann plot to pump air with argon gas in a one-to-half ratio.
Figure 17. Boltzmann plot to pump air with argon gas in a one-to-half ratio. We require the energies of the higher levels, as well as the transition possibilities in the diagrams used for each element, as well as the statistical weights obtained from the global website of the National Institute of Standards and Technology (NIST) database [14]. Whereas, R2 is a statistical parameter indicating the quality of the linear match, which takes a value of (1.0). And the best of it is closest to 1. Using the stark broadening equation, the electron density was calculated as shown in the following figures. The stark broadening of spectral lines in the plasma results from collisions with the charged species, resulting in line expansion and a shift in the peak wavelength.

Figure 18. Variation in the signal intensity and width of argon gas.
The values of the electron temperatures calculated with the Boltzmann equation, the results appear as the value of the flow rate in the reactor increases, the electron temperature decreases. The reason is that, as the rate of flow increases, the collisions of electrons within the arc increase and the electron temperature decreases.
Figure 22. The variation of \( T_e \) and \( n_e \) for argon gas

Figure 23. The variation of \( T_e \) and \( n_e \) for air with argon gas in a one-to-one ratio.

Figure 24. The variation of \( T_e \) and \( n_e \) for air with argon gas in a one-to-half ratio.
Figure 25. The variation of $(T_e)$ and $(n_e)$ for of air with argon gas in a one-to-quarter ratio.

The following tables show the calculated electron temperature ($T_e$), electron density ($n_e$), Debye length ($D$). As well as information on the resulting plasma.

**Table 1** Thermal properties for argon gas.

| Flow (L/min) | $T_e$ (eV) | FWHM (nm) | $n_e \times 10^{17}$ (cm$^{-3}$) | $f_p (Hz) \times 10^{12}$ | $\lambda_D \times 10^6$(cm) | $N_D$ |
|--------------|------------|-----------|-------------------------------|--------------------------|--------------------------|------|
| 6            | 1.341      | 0.600     | 4.054                         | 5.718                    | 1.351                    | 4    |
| 8            | 1.120      | 0.700     | 4.730                         | 6.176                    | 1.144                    | 3    |
| 10           | 1.048      | 0.750     | 5.068                         | 6.393                    | 1.069                    | 3    |
| 12           | 0.974      | 0.800     | 5.405                         | 6.602                    | 0.997                    | 2    |
| 14           | 0.888      | 0.800     | 5.405                         | 6.602                    | 0.953                    | 2    |

**Table 2** Thermal properties for mix air with argon gas for one-to-one ratio.

| Flow (L/min) | $T_e$ (eV) | FWHM (nm) | $n_e \times 10^{17}$ (cm$^{-3}$) | $f_p (Hz) \times 10^{12}$ | $\lambda_D \times 10^6$(cm) | $N_D$ |
|--------------|------------|-----------|-------------------------------|--------------------------|--------------------------|------|
| 10           | 1.337      | 1.000     | 6.757                         | 7.382                    | 1.045                    | 3    |
| 14           | 1.184      | 1.100     | 7.432                         | 7.742                    | 0.938                    | 3    |
| 20           | 1.170      | 1.150     | 7.770                         | 7.916                    | 0.912                    | 2    |
| 26           | 1.014      | 1.200     | 8.108                         | 8.086                    | 0.831                    | 2    |
| 30           | 1.019      | 1.200     | 8.108                         | 8.086                    | 0.833                    | 2    |
Table 3 Thermal properties for mix air with argon gas for one-to-half ratio.

| Flow L/min | Te (eV) | FWHM (nm) | n_e x 10^{17} (cm^{-3}) | f_p (Hz) x 10^{12} | λ_D x 10^{-6} (cm) | N_D |
|------------|--------|-----------|--------------------------|-------------------|-------------------|-----|
| 8          | 1.706  | 1.200     | 7.500                    | 7.777             | 1.120             | 4   |
| 11         | 1.551  | 1.230     | 7.688                    | 7.874             | 1.056             | 4   |
| 15         | 1.488  | 1.260     | 7.875                    | 7.969             | 1.021             | 4   |
| 19         | 1.458  | 1.300     | 8.125                    | 8.094             | 0.995             | 3   |
| 22         | 1.213  | 1.300     | 8.125                    | 8.094             | 0.908             | 3   |

Table 4 Thermal properties for mix air with argon gas for one-to-quarter ratio.

| Flow L/min | Te (eV) | FWHM (nm) | n_e x 10^{17} (cm^{-3}) | f_p (Hz) x 10^{12} | λ_D x 10^{-6} (cm) | N_D |
|------------|--------|-----------|--------------------------|-------------------|-------------------|-----|
| 6          | 1.843  | 1.100     | 6.875                    | 7.446             | 1.217             | 5   |
| 9          | 1.762  | 1.200     | 7.500                    | 7.777             | 1.139             | 5   |
| 13         | 1.616  | 1.250     | 7.813                    | 7.937             | 1.068             | 4   |
| 17         | 1.546  | 1.350     | 8.438                    | 8.249             | 1.006             | 4   |
| 20         | 1.362  | 1.350     | 8.438                    | 8.249             | 0.944             | 3   |

Tables 1-4 shows the calculated electron temperature (T_e), electron density (n_e), Debye length (λ_D) by using equation [20],

\[
\lambda_D = \left[ \frac{\varepsilon_0 K_B T_e}{n_e e^2} \right]^{1/2} \approx 7.43 \times 10^{2} \left( \frac{T_e (\text{eV})}{n_e} \right)^{1/2}
\]  

(1)

Plasma frequency (f_p) using equation [16,17],

\[
\omega_{pe} = \left( \frac{n_e e^2}{m_e \varepsilon_0} \right)^{1/2}
\]

(2)

And Debye number (ND) using equation [18,19],

\[
N_D = \frac{4}{3} \pi n_e \lambda_D^3
\]

(3)

4. Conclusion

In this paper, a system for RVF-GA plasma was designed using locally available and low-cost materials. Based on previous research, pure argon gas was pumped at various flow rates to ensure the reactor's operation and to obtain an ideal gliding arc. The nitrogen gas was then mixed with air, which is an
innovative way to obtain nitrogen gas at low cost and with ease of availability. It was mixed in various proportions with Argon to obtain the greatest amount of nitrogen, which can be used in a variety of applications. The spectral properties of the resulting arc, such as an electron's heat, were then studied using the Boltzmann equation, and the electron density using the Stark-broadening equation. The results we obtained are ideal for thermal insulation, which is the goal of creating a rotating gliding arc where the external wall of the reactor can be touched with hand, and the system was remarkably stable, with high energy consumption gathered in the reactor's center away from the walls. As it is produced in agricultural applications, the system's work has a promising future. Through nitrogen oxidation, natural plant fertilizer can be produced without the use of any industrial substances.

References
[1] Hati, S., Mandal, S., Vij, S., Minz, P.S., Basu, S., Khetra, Y., Yadav, D. and Daihya, M., 2012. Nonthermal plasma technology and its potential applications against foodborne microorganisms. Journal of Food Processing and Preservation, 36(6), pp.518-524.
[2] Kolev, S. and Bogaerts, A., 2014. A 2D model for a gliding arc discharge. Plasma Sources Science and Technology, 24(1), p.015025.
[3] Korolev, Y.D., Frants, O.B., Geyman, V.G., Landl, N.V. and Kasyanov, V.S., 2011. Low-current “gliding arc” in an air flow. IEEE Transactions on Plasma Science, 39(12), pp.3319-3325
[4] Trelles, J.P., 2020. Nonequilibrium phenomena in (quasi-) thermal plasma flows. Plasma Chemistry and Plasma Processing, 40(3), pp.727-748.
[5] Ralchenko, V., Sychov, I., Vlasov, I., Vlasov, A., Konov, V., Khomich, A. and Voronina, S., 1999. Quality of diamond wafers grown by microwave plasma CVD: effects of gas flow rate. Diamond and related materials, 8(2-5), pp.189-193.
[6] Laroussi, M. and Akan, T., 2007. Arc – free atmospheric pressure cold plasma jets: A review. Plasma Processes and Polymers, 4(9), pp.777-788.
[7] Bogaerts, A., Berthelot, A., Heijkers, S., Kolev, S., Snoeckx, R., Sun, S., Trenchev, G., Van Laer, K. and Wang, W., 2017. CO2 conversion by plasma technology: insights from modeling the plasma chemistry and plasma reactor design. Plasma Sources Science and Technology, 26(6), p.063001.
[8] Devia, D.M., Rodriguez-Restrepo, L.V. and Parra, E.R., 2015. Methods employed in optical emission spectroscopy analysis: a review. Ingeniería y ciencia, 11(21), pp.239-267.
[9] Lu, S.Y., Sun, X.M., Li, X.D., Yan, J.H. and Du, C.M., 2012. Physical characteristics of gliding arc discharge plasma generated in a laval nozzle. Physics of Plasmas, 19(7), p.072122.
[10] Ananthanarasimhan J., Lakshminarayana R., Anand M. S., Dasappa S., 2019. Observation of arc rotation and voltage characteristics in rotating gliding arc. 24th International Symposium on Plasma Chemistry, Nepal.
[11] Sasu, K., Dussadee, N. and Tippayawong, N., 2019. Overview of tar reduction in biomass-derived producer gas using non-thermal plasma discharges. Maejo International Journal of Science and Technology, 13(1), pp.42-61.
[12] Ahmed, A.N., Alwazzan, M.J. and Ismael, M.A., 2020. Study Effects of Pulse Laser Energy on Human Primary Teeth and Extraction Caries Area by Using Image Processing Techniques. NeuroQuantology, 18(6), p.36.
[13] Sandeep, S., 2012. Investigations of nonlinear optical effects and ultrafast laser Induced plasma in nanostructured media (Doctoral dissertation).
[14] Zhukov, M.F. and Ovsyannikov, A.A., 2005. Plasma Diagnostics, Ch. 5. UK: Cambridge International Science Publishing.
[15] Hamed, S.S., 2005. Spectroscopic determination of excitation temperature and electron density in premixed laminar flame. Egypt. J. Solids, 28(2), pp.349-357.
[16] Sandeep, S., 2012. Investigations of nonlinear optical effects and ultrafast laser Induced plasma in nanostructured media (Doctoral dissertation).
[17] Gurnett, D.A. and Shaw, R.R., 1973. Electromagnetic radiation trapped in the magnetosphere above the plasma frequency. Journal of Geophysical Research, 78(34), pp.8136-8149.
[18] Morozov, A.A., Evtushenko, A.B. and Bulgakov, A.V., 2015. Gas-dynamic acceleration of laser-
[19] ablation plumes: Hyperthermal particle energies under thermal vaporization. Applied Physics
Letters, 106(5), p.054107.
Debye number (ND) using equation.
[20] Stenson, E.V., Horn-Stanja, J., Stoneking, M.R. and Pedersen, T.S., 2017. Debye length and
plasma skin depth: two length scales of interest in the creation and diagnosis of laboratory pair
plasmas. Journal of Plasma Physics, 83(1).