Evolution and Characterization of Arc Plasma Under Atmospheric Pressure

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Abstract. This work elucidates the evolution of Arc plasma and its characterization in terms of different plasma parameters under atmospheric pressure. The I-V traits of Langmuir probes are plotted from the experiment for a single probe approach in Arc plasma. It is discovered that the silica seed alters the electron temperature of the plasma substantially, while the temperature of the gas in the surrounding remains nearly unchanged. The single probe traits were applied to find the electron temperature, floating potential, Debye length and electron density. It is perceived that electron density increases substantially, while electron temperature is reduced after seeding the Arc plasma. A large fall in electron temperature an unusual growth in electron density which is discovered after mixing the plasma with silica aggregate in comparison to those before mixing. The effect of discharge voltage on plasma frequency and Debye length is also mentioned.

Keywords: evolution, Arc plasma, langmuir probe, silica, seeding

Introduction

Arc plasma has a large number of applications in plasma research (Lobbia and Beal, 2017). Cold atmospheric pressure plasma (CAPP) is important for its anticancer properties (Bania *et al*., 2021). Measurement of Plasma Parameters (Thakur *et al*., 2019; Dolai and Prajapati, 2017; Mishra *et al*., 2004) is very important for industrial actions such as plasma processing (Ben Salem *et al*., 2014; Brockhaus *et al*., 1994). Mixing of heterogeneous catalysts and their role in a regular operation for plasma waste treatment (Olszewskia *et al*., 2014; Mizuno *et al*., 1992), plasma methane conversion (Francke *et al*., 2000) and other applications of plasmas (Lupan *et al*., 2010; Bromberg *et al*., 1998; Kizling and Jaras, 1996; Schmidt-Szalowski *et al*., 1990). Electron temperature (T_e), electron density (n_e), ion density (n_i) and floating potential (V_f) are estimated using Langmuir Probe (Gruenwald *et al*., 2018). In this work, low voltage Arc discharge has been utilized for the estimation of electron temperature under the influence of silica seeding. In this paper, we have presented the evidence for non equilibrium of low-temperature plasma with silica (SiO_2) in presence of Al_2O_3 (2% by weight). Arc plasma is commonly called low temperature and high density plasma. But inner temperature is enough to melt the probe and kept in it for some time. This problem is solved by using an oscillating probe so, that it may remain in the Arc for a fraction of a second. Single probe characteristics have been employed to determine the plasma parameters in the Arc plasma before and after seeding. Plasma parameters before and after seeding, the Arc plasma are compared and dependence of T_e, ne, Debye length (λ_D) and plasma frequency (f) on discharge voltage, in the seeded Arc plasma are also studied.

The experimental arrangement is described in Material and Method. Theory, results and their discussions are presented in separate parts. Finally, a brief summary is given in the Conclusion.

Material and Methods

Experimental design and setup. The basic circuit of the experimental arrangement is depicted in Fig. 1. An Arc plasma is ignited between horizontal copper electrodes when a dc voltage (0-600 V) is applied across the electrodes. The probe (tungsten wire) is kept oscillating between the electrodes through the Arc plasma. The oscillation is done with the help of an electric motor of 25-watt power. A significant part of the probe is covered by an insulating fibre and a biasing dc voltage of (0-60 V) is applied, which is used for dragging electrons and ions for the I-V curve. The values of

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electron current (I_e) and ion current (I_i) are noted with the help of deflection on a ballistic galvanometer.

An empty quartz vessel (small bowl) is placed just below the Arc. For the measurement of parameters in Arc plasma before seeding, the bowl is kept empty throughout the experiment. During the seeding, the vessel is filled with a dry sample of silica mixture. In the beginning, there was a fluctuation in the probe current after seeding but after 35 min, the stability in the probe current was observed. A new set of data was then taken for the I-V curve of the single probe method in silica seeded Arc plasma. The detailed descriptions of the electrodes and the probe are given in Table 1.

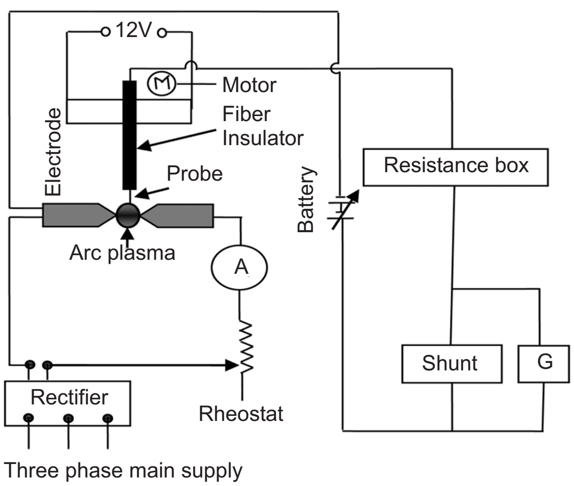

Fig. 1. Basic circuit for single probe method.

Table 1. Specifications of the electrodes and probe

Electrode material	Copper
Length of the probe	1.60 mm
Average diameter of the probe	0.90 mm
Diameter of each electrode	5.52 mm
Surface area of the probe (A)	5.16×10^{-6} m^2
Average diameter of the Arc	8.23 mm
Average speed of the probe	20.07 mm/s
Passage time of the probe through the Arc	0.41 s
Maximum probe current	0.52 mA
Probe material	Tungsten

Theory. The fundamental equations of cylindrical Langmuir probe for single probe method (SPM) are as follows (Fauchais, 1984):

$$I_e = \frac{n_e e A}{2}\left(\frac{2kT_e}{\pi m_e}\right)^{1/2} \exp(-eV/kT_e) \quad .... (1)$$

where:

$V = 0$ and $I_e = (I_e)_r$ and so, we can write

$$n_e = \frac{(I_e)_r}{eA}\left(\frac{2\pi m_e}{kT_e}\right)^{1/2} \quad .... (2)$$

In the above expression; I_e is the current in the probe due to electron; I_i the current in the probe due to ions; n_e is the electron density; e is the charge on the electron; A is the surface area of the probe; k the Boltzmann's constant; T_e the electron's temperature; m_e is the mass of the electron; m_i is the mass of ions and V the probe's potential. Equation (1) is used for calculating the value of T_e by drawing a tangent to the ln I_e versus V curve of the probe. By knowing T_e, one can obtain the value of n_e using equation (2). For a sufficiently negative probe potential, a stage comes when I_e just cancels I_i,

where:

$V = V_s$; V_s represents the space potential. The Langmuir probe technique is suitable for the study of plasma of moderate density.

Results and Discussion

Figure 2(a) shows the plot of probe current (ln I) with probe potential (V) before seeding the Arc. The current (I) is in μA. The positive part of this curve represents electron current while the negative part of the curve represents ion current for different voltages applied to the probe. The floating potential is found to be –39 V. Fig. 2(b) shows the linear fit for the determination of electron temperature before seeding. The best-fit equation for this line is given below:

$$\ln I = 0.16V + 6.23$$

The slope of this line is used for calculating T_e. The values of T_e and n_e in the Arc plasma are estimated to be 6.25 eV and 2.11×10^{13} m^{-3}, respectively.

Figure 3(a) shows the I-V characteristics of the single probe method for the Arc plasma seeded with a silica mixture. From this curve, the floating potential is observed to be about -34 V after seeding.

Figure 3(b) shows the linear fit for the determination of electron temperature after seeding the plasma. The best fit equation for this line is given below:

$$\ln I = 0.85\ V + 29.13$$

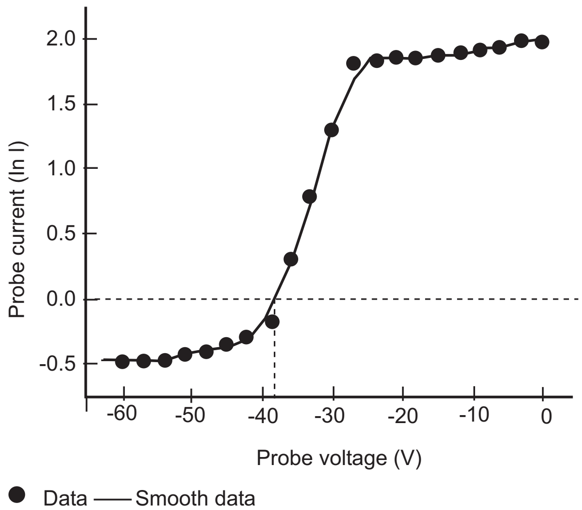

Fig. 2a. I-V Characteristics for single probe method before seeding.

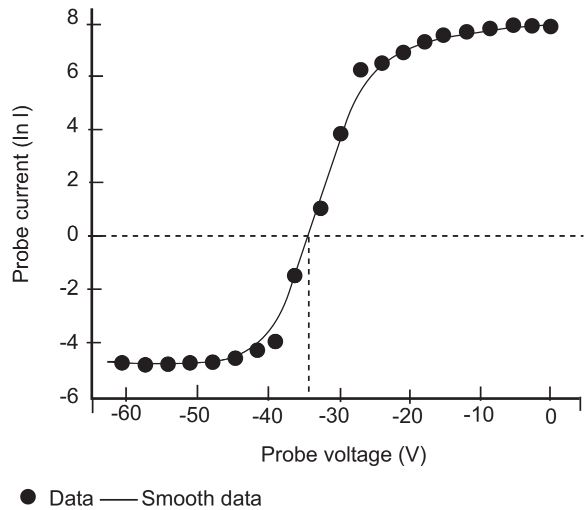

Fig. 3a. I-V Characteristics for single probe method after seeding.

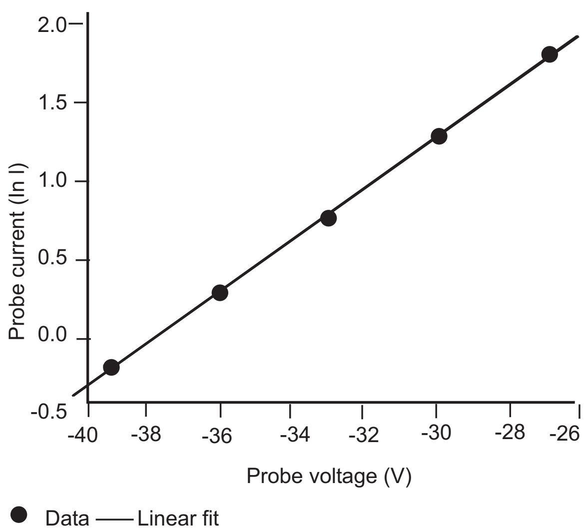

Fig. 2b. Linear fit for electron temperature before seeding.

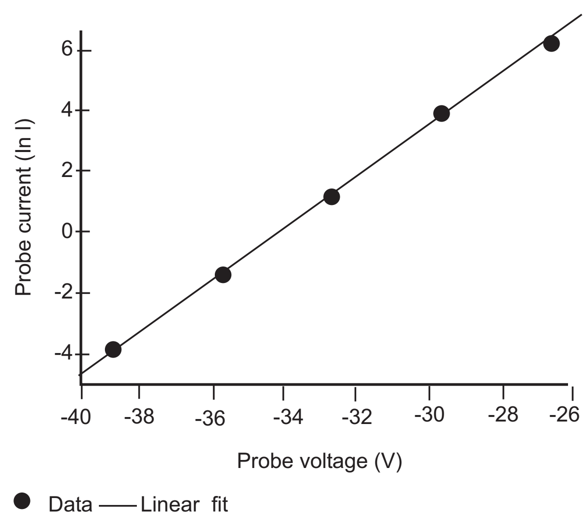

Fig. 3b. Linear fit to calculate electron temperature after seeding.

After seeding the Arc plasma, the value of T_e decreases to 1.18 eV, while the value of n_i increases to $1.84\times10^{16}/m^3$. In other words, there is an appreciable fall in electron temperature after seeding and an increase in electron density to 99.9% as compared to that before seeding. The silica enhanced non-equilibrium of cold plasmas is related to the promoter alumina (Al_2O_3) loaded into the silica. It is clear that the silica mixture effectively enhances the non- equilibrium of the plasma.

The dependence of T_e on discharge voltage in silica seeded Arc plasma is plotted in Fig. 4. As discharge voltage increases, the value of T_e increases. The increase in electron temperature is due to the gain in kinetic energy of the electrons from the electric field.

The electrons gain more energy if the discharge voltage is higher. The ionizing activity increases inside the plasma due to dominant inelastic collisions between electrons with a gradual increase in discharge potential and finally, it results in the increment of electron temperature. The electron temperature in the Arc plasma, therefore, rises with the increase in discharge potential.

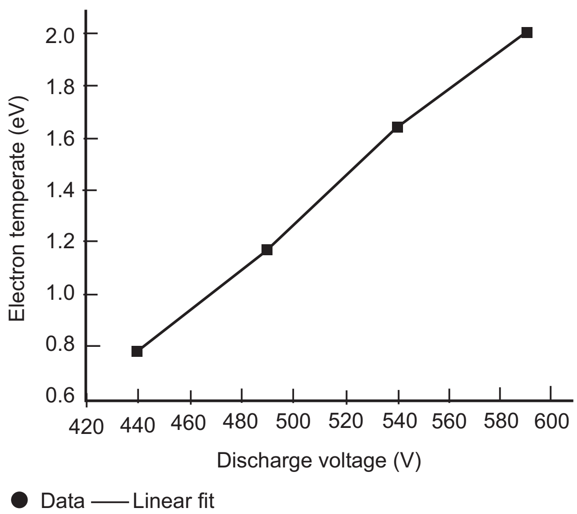

Fig. 4. Dependence of electron temperature on discharge voltage.

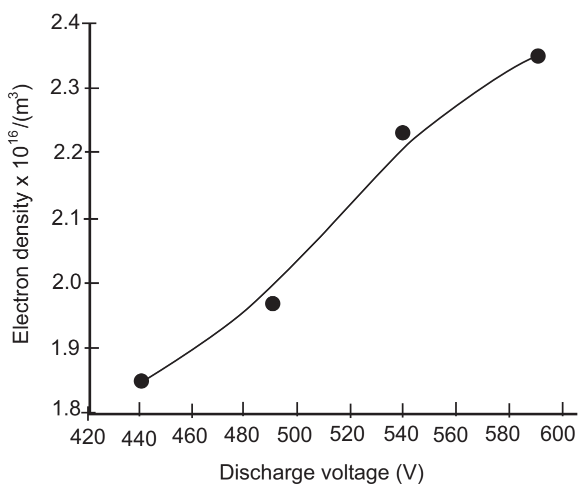

Fig. 5. Dependence of electron density on discharge voltage.

A typical variation profile of electron density with discharge voltage is shown in Fig. 5. When discharge voltage increases, the speed of electron also increases due to which electron concentration also increases.

Figure 6 shows the plot of plasma frequency with discharge voltage. The plasma frequency is the frequency at which the electron cloud aways with respect to the ion cloud. This property totally depends upon the number of electrons per unit volume. As there is an increase in discharge voltage, the electron concentration also increases. Subsequently, plasma frequency increases in case discharge voltage increases.

The reliance of Debye length on discharge voltage is shown in Fig. 7. It is a measure of the distance that the potential of a charged object penetrates into the plasma. It depends upon the temperature and concentration of electrons.

At higher discharge voltage, electrons become more energetic. A few of them can enter the positive sheath region and reduce the number of positive ions. Consequently, there is a decrease in the Debye length of the plasma with the increase in discharge voltage.

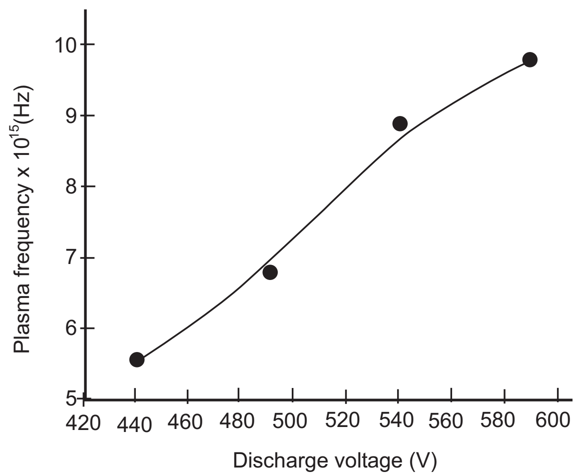

Fig. 6. Dependence of plasma frequency with discharge voltage.

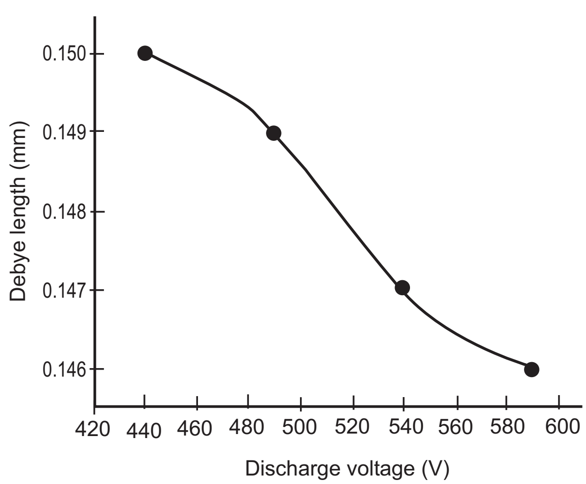

Fig. 7. Dependence of Debye length with discharge voltage.

Conclusion

From the present research, it is obvious that the single probe method is a reliable method for characterization of Arc plasma. The plasma parameters obtained before seeding the Arc plasma are in agreement with the order of those obtained by other researchers at atmospheric pressure. The very large decrease in electron temperature and increase in electron density in the Arc plasma as a result of silica seeding is really interesting. An increase in electron temperature, electron density and plasma frequency but a decrease in Debye length with an increase in discharge voltage is found in the experiment. This study can be extended with modifications for measuring of useful plasma parameters to improve the various plasma processing and other industrial applications of plasma, such as the production of efficient plasma torch. The study of Arc plasma is also important for fusion technology.

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Conflict of Interest. The authors declare they have no conflict of interest.

References

Bania, H.B., Khadka, P., Pandey, S., Nepal, A., Guragain, P., Lamichhane, T.R., Dhungana, S., Shrestha, B.G., Subedi, D.P. 2021. Characterization of cold atmospheric pressure plasma technology and its anticancer propeties. *Plasma Medicine*, **11:** 53-62.

Ben Salem, D., Carton, O., Fakhouri, H., Pulpytel, J., Arefi-Khonsari, F. 2014. Deposition of water stable plasma polymerized acrylic acid/MBA organic coatings by atmospheric pressure air plasma jet. *Plasma Processes and Polymers*, **11:** 269-278.

Brockhaus, A., Borchardt, C., Engemann, J. 1994. Langmuir probe measurements in commercial plasma plants. *Plasma Sources Science Technology*, **3:** 539-544.

Bromberg, L., Cohn, D.R., Rabinovich, A. 1998. Plasma reforming of methane. *Energy Fuels*, **12:** 11-18.

Dolai, B., Prajapati, R.P. 2017. Rayleigh-taylor instability and internal waves in strongly coupled quantum plasma. *Physics of Plasmas*, **24:** 112101.

Fauchais, P. 1984. Applications physico-chemiques des plasma de'Arc. *Reviews Physics Application (Paris)*, **19:** 1013-1045.

Francke, K.P., Miessner, H., Rudolf, R. 2000. Plasma catalytic processes for environmental problems. *Cataysis Today*, **59:** 411-416.

Gruenwald, J., Reynvaan, J., Geistlinger, P. 2018. Basic plasma parameters and physical properties of inverted He fireball. *Plasma Sources Science and Technoogy*, **27:** 015008.

Kizling, M.B., Jaras, S.G. 1996. A review of the use of plasma techniques in catalyst preparation and catalytic reactions. *Applied Catalysis A*, **147:** 1- 21.

Lobbia, R.B., Beal, B.E. 2017. Recommended practice for use of Langmuir probes in electric propulsion testing. *Journal of Propulsion and Power*, **33:** 566-581.

Lupan, O., Pauporte, T., Chow, L., Viana, B., Pelle, F., Ono, L.K., Roldan, C.B., Heinrich, H. 2010. Effects of annealing on properties of ZnO thin films prepared by electrochemical deposition in chloride medium. *Applied Surface Science*, **256:** 1895-1907.

Mishra, L.N., Shibata, K., Ito, H., Yugami, N., Nishida, Y. 2004. Characteristics of electron cyclotron resonance plasma generated in a rectangular wave guide by high power microwave. *Review of Scientific Instruments*, **75:** 84-89.

Mizuno, A., Yamazaki, Y., Ito, H., Yoshida, H. 1992. AC energized ferroelectric pellet bed gas cleaner. *IEEE Transactions on Industry Applications*, **28:** 535-540.

Olszewskia, P., Li, J.F., Liub, D.X., Walsh, J.L. 2014. Optimizing the electrical excitation of an atmospheric pressure plasma advanced oxidation process. *Journal of Hazardous Materials*, **279:** 60-66.

Schmidt-Szalowski, K., Borucka, A., Jodzis, S. 1990. Catalytic activity of silica in ozone formation in electrical discharges. *Plasma Chemistry and Plasma Processing*, **10:** 443-450.

Thakur, G., Khanal, R., Narayan, B. 2019. Characterization of Arc plasma by movable single and double Langmuir probes. *Fusion Science and Technology*, **75:** 324-329.