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# Impact of silica seeding and discharge voltage on plasma parameters at atmospheric pressure

Vijay Kumar Jha[1],Lekha Nath Mishra[2]*,Bijoyendra Narayan[3]

**Abstract**
The interaction of cold plasma with heterogeneous catalysts has led to some peculiar behavior, especially with silica ($SiO_2$) seeding in presence of 2% alumina ($Al_2O_3$). In this paper, we have measured plasma parameters in low temperature arc plasma. I - V characteristics of Langmuir probes are plotted using the data obtained from the experimental set up for single probe method in arc plasma at atmospheric pressure. It is revealed that the used seed modifies the electron temperature of the plasma appreciably while the temperature of the gas in the surrounding remains almost unchanged. The single probe characteristics have been utilized to measure the electron temperature, floating potential, Debye length and electron density. It is found that electron temperature decreases whereas electron density increases appreciably after seeding the arc plasma. The decrease in electron temperature and increase in electron density to 99.9% are observed after seeding the arc plasma with silica mixture as compared to those before seeding. Variations in plasma parameters such as electron temperature, electron density, plasma frequency and Debye length with discharge voltage are also plotted for the silica seeded arc plasma.

**Keywords**
Arc plasma, Debye length, Plasma frequency, Electron density, Langmuir probes.

[1] *Central Department of Physics, Kirtipur (Tribhuvan University, Kathmandu), Nepal*
[2] *Patan Multiple Campus, Patandhoka, Lalitpur (Tribhuvan University, Kathmandu), Nepal*
[3] *J. L. College, Hajipur, Vaishali (B. R. A. Bihar University, Muzaffarpur), India*
***Corresponding author**: lekha.mishra@pmc.tu.edu.np

## 1. Introduction

Measurement of Plasma Parameters [1–3] is very important for the industrial applications such as plasma processing [4,5]. Combination of heterogeneous catalyst and plasmas is becoming a normal operation for plasma waste treatment [6,7], plasma methane conversion [8] and other applications of plasmas [9–12]. Plasma parameters such as electron temperature ($T_e$), electron density ($n_e$), ion density ($n_i$) and floating potential ($V_f$) are estimated using Langmuir Probe [13]. In this work, atmospheric pressure plasma arc discharge has been applied for the measurement of electron temperature under the influence of a heterogeneous catalyst. An important characteristic of cold plasma is its high electron temperature of the order of $10^4$ K while the temperature of the gas remains low in the surrounding. The non - equilibrium of the cold plasma is thereby addressed. We present direct experimental evidence for catalyst enhanced non - equilibrium of low temperature plasmas, especially, with silica in presence of $Al_2O_3$ (2 % by weight). Arc plasma [2, 14] constitutes a separate branch in plasma research with wide range of applications. Arc plasma is known as low temperature and high density plasma. However, its inner temperature is adequate to melt the probe when kept in it for some time. This problem is solved by using moving probe so that it may remain in the arc, especially in the hottest zone, for a fraction of a second. Single probe characteristics have been employed in the present study to determine the plasma parameters in the arc plasma before and after seeding it with heterogeneous impurity. The plasma parameters before and after seeding the arc plasma are compared. Dependence of plasma parameters such as electron temperature, electron density, Debye length and plasma frequency with discharge voltage, in seeded arc plasma are also studied.

The paper is organized as follows. The experimental set up is described in section II. The theory is mentioned in section III. The results and their discussions are presented in section IV. Finally, a brief summary (conclusions) is given in section V.

## 2. Experimental set up

The schematic diagram of the experimental set up for single probe method is shown as in Fig. 1. An arc plasma is ignited between two copper electrodes when dc voltage (0 – 600 V) is applied on the electrodes. The movable cylindrical probe (tungsten wire) is kept moving between the electrodes. The major portion of the probe is covered by insulating fiber. The biasing dc voltage (0 - 60 V) on the probe is used to drag the electron as well ions for the $I-V$ characteristics. The electron and ion current are noted with the help of deflection

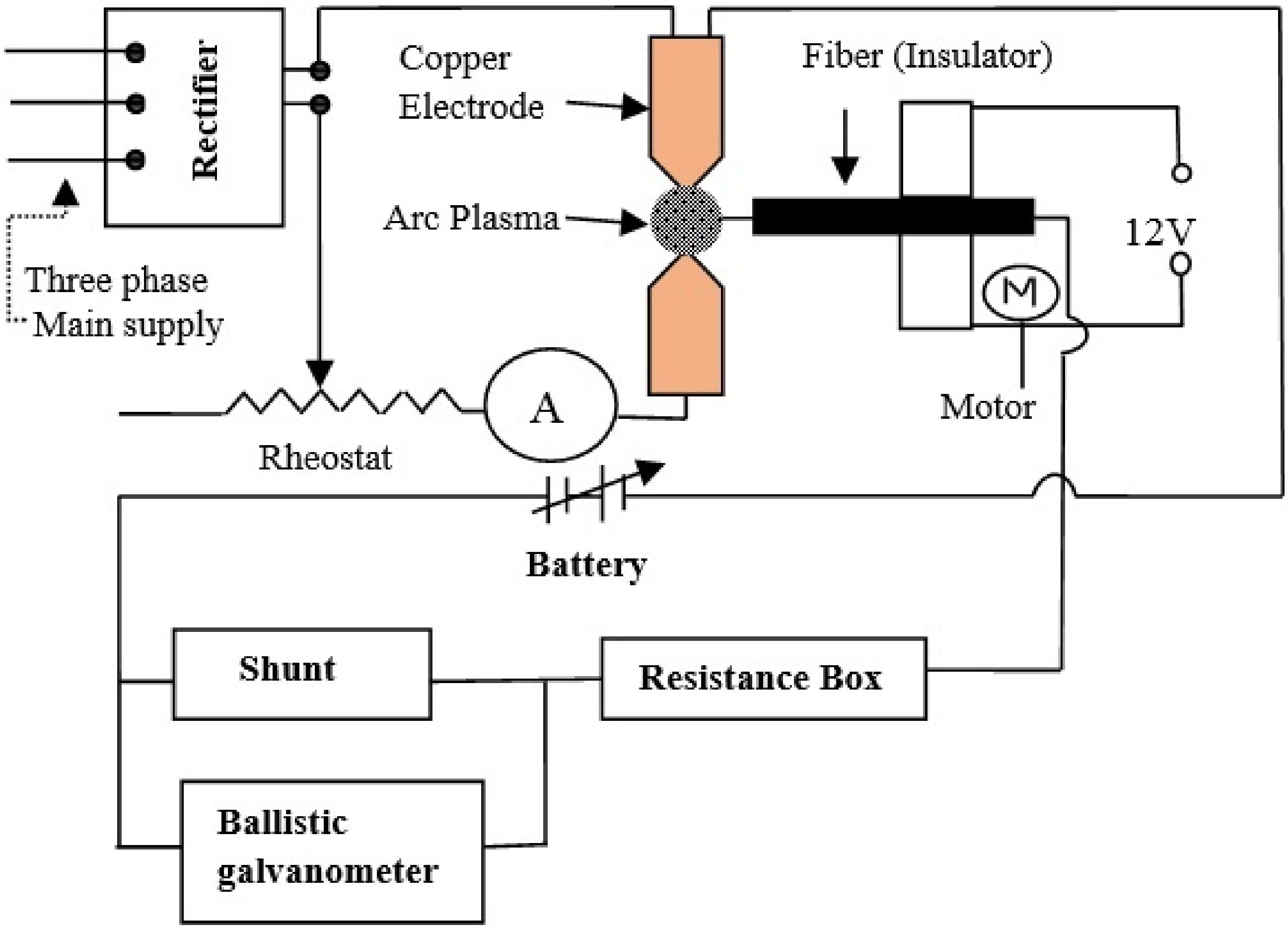


**Figure 1.** Basic circuit for single probe method.

**Table 1.** Specifications of the probe and electrodes.

| | |
|---|---|
| Probe material | Tungsten |
| Probe length | 1.60 mm |
| Average radius of the probe | 0.45 mm |
| Diameter of the electrode | 5.52 mm |
| Surface area of the probe ($A$) | $5.16 \times 10^{-6}$ m$^2$ |
| Average diameter of the arc | $8.23 \times 10^{-3}$ m |
| Average velocity of the probe | 20.07 mms$^{-1}$ |
| Passage time of the probe through the arc | 0.41 s |
| Maximum probe current | 0.52 mA |
| Electrode material | Copper |

on ballistic galvanometer. Specification of the probe and electrode are shown in Table 1.

## 3. Theory

The elementary theory of collecting Langmuir probe is based on cylindrical geometries. The basic equations for Langmuir probe (single probe method) are [15] as follows:

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

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

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

and also

$$n_i \approx \frac{2.5 I_i}{eA}\left(\frac{m_i}{2kT_e}\right)^{\frac{1}{2}} \quad (3)$$

where $I_e$ is the current in the probe due to electron, $I_i$ the

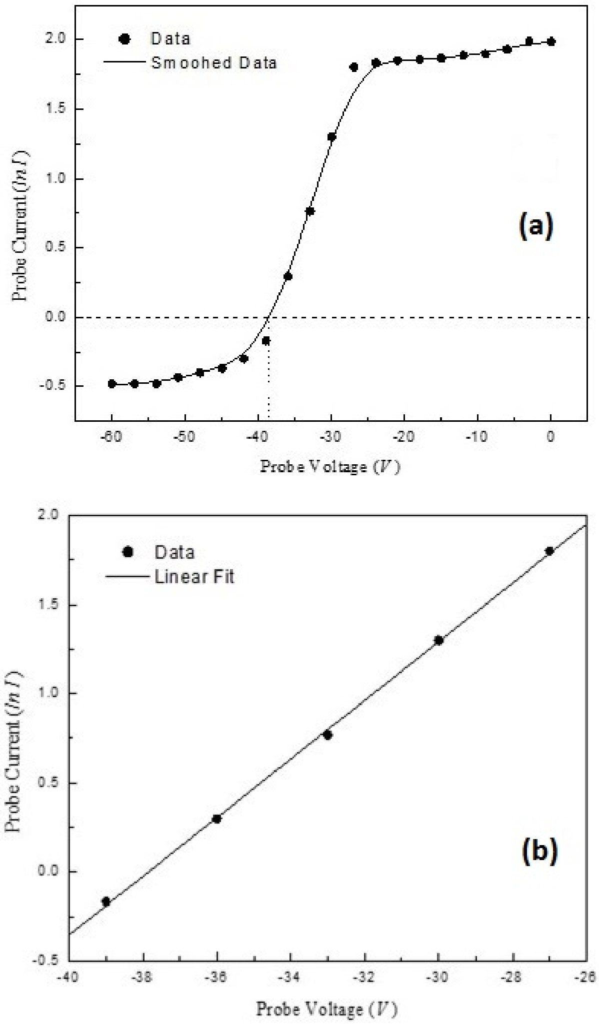


**Figure 2.** (a) Basic circuit for single probe method. (b) basic circuit for single probe method.

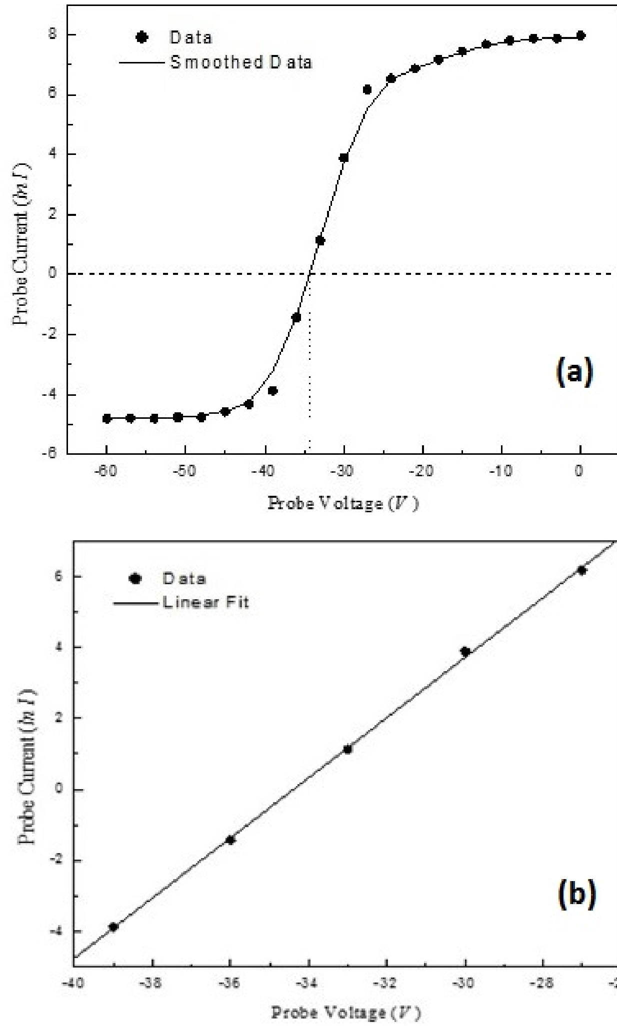


**Figure 3.** (a) Basic circuit for single probe method. (b) linear fit for the determination of electron temperature after seeding.

current in the probe due to ions, $n_e$ the electron density, $n_i$ the ions density, $e$ the charge on electron, $A$ the surface area of the probe, $k$ the Boltzmann's constant, $T_e$ the electron's temperature, $m_e$ the mass of electron, $m_i$ the mass of ions and $V$ the probe's potential. Equation (1) is used for the determination of electron temperature ($T_e$) by drawing tangent to the curve ln $I_e$ versus $V$ of the probe. Once the electron temperature is found, one can obtain the electron density using equation (2) and then ion density in the plasma using equation (3). For a sufficiently negative probe potential, a stage comes when the electron current drawn just cancels the ion current. This occurs when $V = V_s$. Here, $V_s$ represents space potential. The Langmuir probe technique is useful for study of plasmas of moderate density, if the density is high enough so that electron and ion mean free paths become small, comparable with the dimensions of the probe then the deduction in the paragraphs above is no longer valid [16]. The basic equation to determine the parameter, especially the ion-concentration, of the arc plasma, using DPM [17] is:

$$(\frac{dI}{dV})_0 = [\frac{I_{i1} \times I_{i2}}{I_{i1} + I_{i2}}](\frac{e}{kT_e}) \quad (4)$$

where $I_{i1}$ is the ion-saturation current flowing to one probe, $I_{i2}$ the ion-saturation current flowing to the other probe, $V$ the potential difference applied to the probes and $(\frac{dI}{dV})_0$ the slope of the curve at $I = 0$.

The slope $(\frac{dI}{dV})_0$ and the ion saturation currents $I_{i1}$ and $I_{i2}$ can be calculated by drawing a graph between $I$ and $V$. Using Eq. (1), electron temperature can be calculated. Ion temperature cannot be calculated since it is about one tenth of the electron temperature. The plasma density can be calculated from either of the two parts of the graph using the equations

$$I_i = \frac{1}{2} n_i e A (\frac{kT_e}{M})^{\frac{1}{2}} \quad (5)$$

or

$$n_i = \frac{2I_i}{eA}(\frac{M}{kT_e})^{\frac{1}{2}} \quad (6)$$

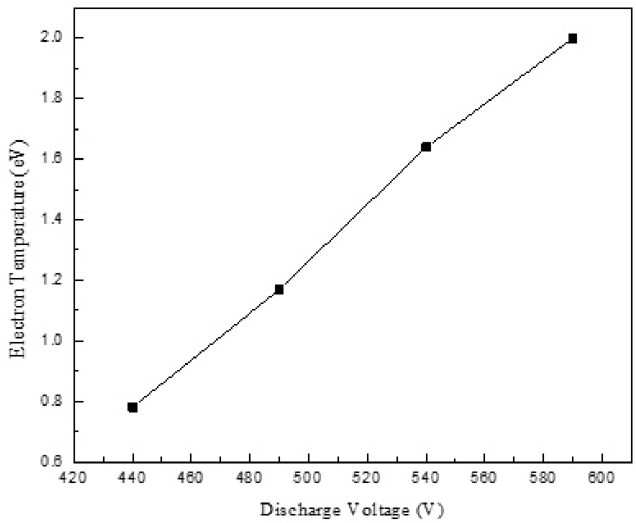


**Figure 4.** Variation in electron temperature with discharge voltage.

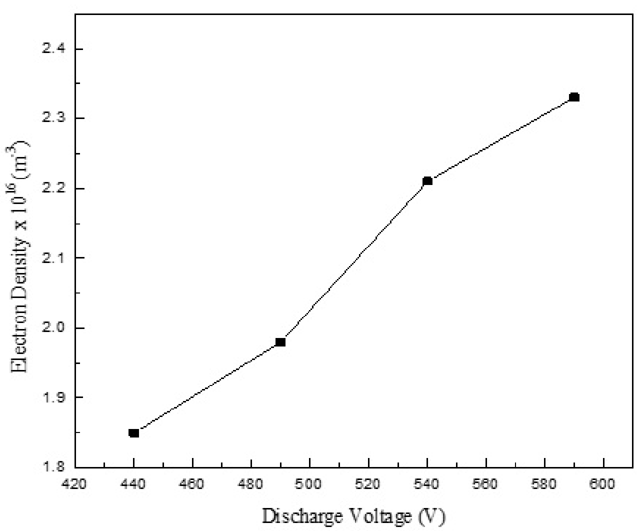


**Figure 5.** Variation in electron density with discharge voltage.

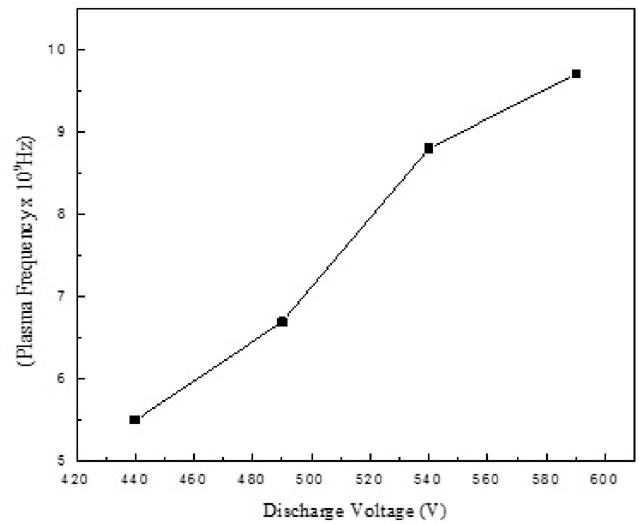


**Figure 6.** Variation in plasma frequency with Discharge voltage.

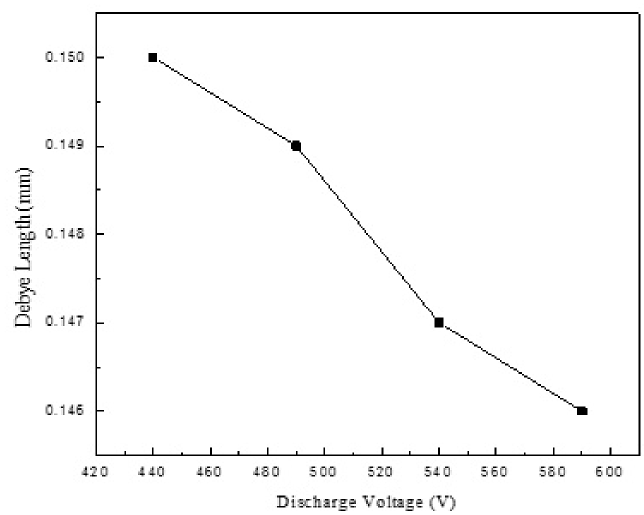


**Figure 7.** Variation in Debye length with discharge voltage.

where, $M$ is mass of the ion and $A$ is the area of the probe. In order to measure the plasma parameters, the tip of Langmuir probe is swept out in the vicinity of arc plasma with the help of electric motor for a short time in such a way that the tip of the probe before and after the experiment remains same.

## 4. Results and discussion

Figure 2 (a) shows the variation in probe current ($lnI$) with probe potential ($V$) before seeding the arc. The current ($I$) is in $\mu A$. 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 by the relation

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

The slope of this line is used for calculating the electron temperature. The electron temperature and electron density in the arc plasma are estimated to be 6.25 eV and $2.11 \times 10^{13}$ $m^{-3}$, respectively.

Figure 3 (a) shows the $I-V$ characteristics of the single probe method for the arc plasma seeded with silica in presence of $Al_2O_3$ (2% by weight). From this curve, the floating potential is observed to be about -34 V after seeding the arc.

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

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

After seeding the arc plasma, it is revealed that the electron temperature decreases to 1.18 eV whereas electron density increases to 1.84 × $10^{16}$ $m^{-3}$. More specifically, there is increase in electron temperature by 429.7% and decrease in electron density to 99.9% as compared to those before seeding. The Silica-enhanced non-equilibrium of cold plasmas is related to the promoter $Al_2O_3$ loaded to the silica. It is obvious that, silica is one of the best catalysts to enhance non-equilibrium of cold plasmas.

Variation of electron temperature with discharge voltage in silica seeded arc plasma is plotted in Fig. 4. As discharge voltage increases the electron temperature of silica seeded arc plasma increases. The increase in electron temperature is due to the increase in kinetic energy of the electrons gained from the electric field.

There is an increase of ionizing activity inside the plasma due to dominant inelastic collisions between electrons with increase in discharge potential and finally, it enhances the increment of electron temperature. The electron temperature and mean energy of electron in the arc plasma, therefore, increase with increase in discharge voltage.

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

Figure 6 refers the variation of plasma frequency with discharge voltage. The plasma frequency is the fundamental property of the plasma and represents the frequency at which the electron cloud oscillates with respect to the ion cloud and it entirely depends upon the plasma density. As the increase in discharge voltage, the electron density also increases. Hence plasma frequency increases with increase in discharge voltage.

Figure 7 shows the variation of Debye length with discharge voltage which is a characteristic scale length in plasma and it is a measure of the distance that the potential of a charged object penetrates into the plasma. It depends upon the electron temperature and electron density.

But on increasing the discharge voltage, electrons become energetic and some of them can enter inside the positive sheath region. As a result, it reduces the number of positive ions and leads to decrease the Debye length of the arc plasma.

## 5. Conclusion

The present research confirms that the Langmuir single probe method is reliable method to determine plasma parameters such as electron temperature andelectron density in seeded arc plasmas. The large decrease in electron temperature and the perceptible increase in electron density of the arc plasma due to the effect of silica seeding in presence of $Al_2O_3$ is much interesting. Langmuir probes are good to estimate plasma parameters in arc plasma using single probe method (SPM). There is increase in electron temperature, electron density and plasma frequency but decrease in Debye length with increase in discharge voltage. The present study can be extended with modifications for measuring useful plasma parameters to improve various plasma processing and other industrial applications of plasma such as production of more efficient plasma torch. Study of arc plasma is also important for tokamak and fusion technology.

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**Conflict of interest statement:**
The authors declare that they have no conflict of interest.

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