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Double Langmuir probe measurement of plasma parameters in a dc glow discharge

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Abstract

In this paper, plasma main characteristics such as electron mean temperature, electron number density, and oscillation frequency have been measured experimentally using the double Langmuir probe diagnostic system. In our experiment, the plasma was generated by applying the low pressure dc glow discharge in several common gases. The experimental results indicated the highest plasma density and oscillation frequency for the plasma originating from argon and the highest mean value of temperature for hydrogen plasma. The experimental results were then confirmed by COMSOL simulator, showing reasonable consistency with the simulations. The data were then used to compare the degree of ionization with the measured plasma parameters.

Keywords: double Langmuir probe, glow discharge, COMSOL simulator

1. Introduction

The dc glow discharge has been extensively used in many applications such as in gas lasers, thin film deposition, etching and surface modification of the materials [1- 3]. For understanding, developing and maintaining such processes, it is desirable to determine the basic plasma characteristics such as electron mean temperature, electron density and oscillations frequency. One of the most widely used methods for the plasma diagnostic is the Langmuir single probe. It was used by Irvin Langmuir in 1924. However, to overcome the limitations caused by the single probe, Johnson and Malter, in 1950, introduced the double probe method for the plasma characterization over a wide range of plasma densities [4- 6]. Electron current could be completely controlled by the ion saturation current so that probe would draw a very little amount of current without disturbing the whole plasma condition. It also enabled the performance of the time as well as the space resolved measurements of plasma parameters; it could even be applied to the electrode less discharge, like microwave discharge. The other important aspect of the double probe is that it measures the characteristics of plasma locally; however, almost all other techniques give information over a large volume of plasma [5, 7, 8]. Another important dimension of of the double probe diagnostic is its simplicity, because it allows us to receive the result quickly, without much experience. In order to clarify our paper, it is fruitful to consider some of the previously conducted investigations. Some studies have been performed in the glow discharge plasma regime; for example, in the reference [9], the non-uniform argon dc glow discharge plasma system has been constructed in a very special design to investigate the effect of varying the tube radius on plasma parameters. Shrestha *et al.*, reported the measurement of electron temperature and electron density, Debye length and plasma frequency in a low pressure DC glow discharge in air, using the Langmuir double probe [10]. Further, Patterson *et al.*, have used the Langmuir probes (LP) extensively to characterize plasma environments produced by radio frequency, pulsed plasma thrusters, and laser ablation in order to examine high-density, high-temperature inhomogeneous plasmas such as those that can be created at the university of Rochester's laboratory for Laser Energetics OMEGA facility [11].

Meanwhile, M B Hopkins reviewed the use of a Langmuir probe system in two GEC cells [12]. The major problems associated with probe diagnostics in a GEC cell have been outlined and discussed. Hyun Jin

Figure 1. (color onlin) The photograph of plasma originated from Nitrogen by glow discharge between anode and cathode.

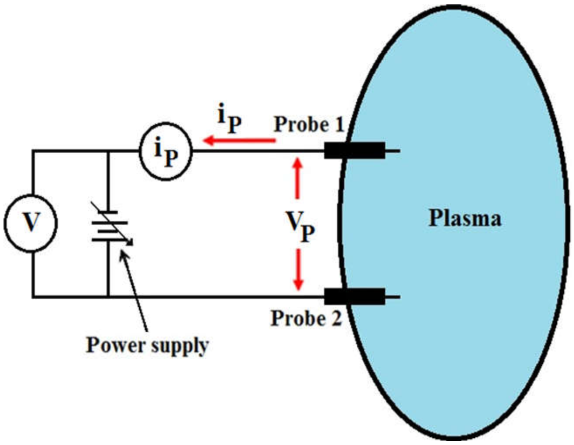

Figure 2. (color onlin) Schematic diagram of the position of probes tips into the plasma.

Yoon *et al.* presents the two- dimensional fluid simulation and the Longmuir probe measurement of a planar inductively coupled oxygen plasma [13]. In ref. [14], by floating the double probe technique in the equivalent resistance method, the plasma parameters have been measured in the subnormal gas discharge. The electron temperature and electron density have been studied in both transversal and longitudinal magnetic fields in the low pressure for air, hydrogen and argon gases. Also, in ref. [15], advanced langmuir probe techniques used for evaluating the plasma potential and electron-energy distribution function (EEDF) in magnetized plasma are reviewed. It is shown that when the applied magnetic field is very weak and the electrons reach the probe without collisions in the probe sheath, the second-derivative Druyvesteyn formula can be used for EEDF evaluation.

All of the above researches have used a few common gases, such as air, oxygen or hydrogen, and the spatial technique for the measurement or simulation in their own experimental conditions. In this paper, we have used a double Longmuir probe to measure the glow discharge plasma density and temperature in a glow discharge chamber for a wide range of well-known gases. Glow discharge chamber is one of the plasma generators or reactors forming plasma in a low pressure gas by applying a rather low voltage between two electrodes inside the gas container. This kind of plasma has wide applications in industries such as environment and medicine, surface treatment, biomedical sciences, pollution control, gas lasers, light source, chemical synthesis, MHD energy converters, and fabrication of electronic circuitry [1, 3]. Different diameters of probe tips and distances between them are examined; after that, according to the characteristic I-V diagrams, the best setup of the probe is defined. Then, the experimental results have been confirmed by COMSOL simulator. The paper is subdivided into four main parts. At first, the experimental set-up and method, the way of measuring plasma parameters from I-V diagram and also, the main formulas for plasma temperature, density and frequency are presented. In the second main section, the simulation method using COMSOL Multiphysics software is explained and its results are discussed. In the third main part, the results and discussions are brought and finally, the conclusions of research are presented in the last part.

2. Experimental set-up and method

The photo of the plasma generator used for the characterization of the typical low pressure dc glow discharge in N_2 is shown in figure 1. In our experiments, vacuum was created at constant pressure inside the discharge tube with about 0.34 mbar and the discharge voltage between the two electrodes was set to be 1kV; it should be noted that for all seven different gases, Ar, He, Ne, N_2, O_2, CO_2 and H_2 molecules, both pressure and voltage were kept constant and all the measurements were performed at the same situation for all gases. Two identical cylindrical probes were inserted in the discharge region between two circular aluminum anodes; also Al cathode with the diameter of about 7 centimeter is presented schematically in figure 2. The data were taken from Tektronix TDS 2014C oscilloscope and transferred to the personal computer through the data storage device for the further analysis. The glow discharge happened in a cylindrical chamber with 18 cm diameter and the length of about 36 cm. The anode and cathode were both in a disc shape; the anode was located at the bottom of the chamber and the cathode was at a distance of about 18 cm above the anode. figure 3 shows the location of anode, cathode and also, the distance between them, as used in our work.

Double Langmuir Diagnostic System (DLPDS) has been used for the experimental measurement of the plasma parameters such as electron temperature, density and electron oscillation frequency. In figure 2, the location of the Langmuir probe in the chamber is shown, where diagnostic probes have a power supply with two conducting electrodes that are put into plasma medium; also, there is a circuit that measures the outcoming current. In double layer probes, the saturated current in both probes is equal and if both probes are fully symmetric, then the characteristic I-V curve will be totally symmetric, as shown in figure 4, so that one can determine the plasma temperature directly from this I-V characteristic plot. In figure 2, the surface of the probes

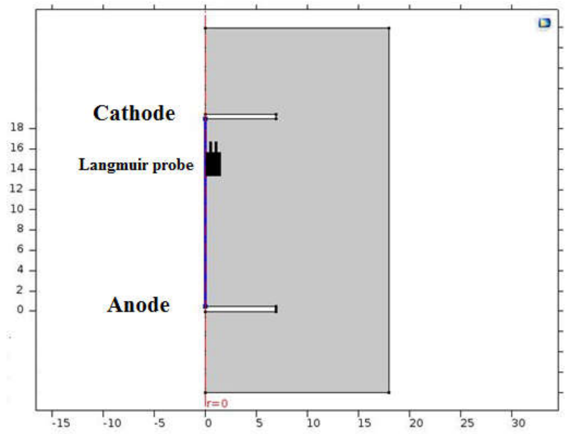

Figure 3. (color online) Typical position of the Langmuir probe in between anode and cathode used for simulation.

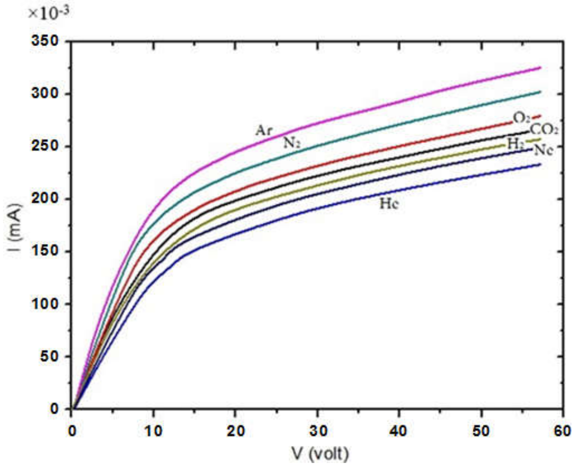

Figure 5. (color online) Experimental characteristic I- V curve for seven different gases.

is fully symmetric and equal to each other. Furthermore, one tip of the probe draws current I_1 and the other one draws current I_2. So, in order to determine the plasma temperature profile, both probes tips should be inserted in several points of the plasma for each of 7 gases and one should work on the plasma floating potential V_f. It means that applying the external potential from the power supply should be equal to the plasma potential V_f. After that, by comparing these several points for each gas, those which have the maximum density and temperature have been chosen. Moreover, the mathematical formula between the current and voltage of the two-arry Langmuir probe is as follows [1],

$$I_1 = I_{1is} - I_{1es} \exp[\frac{e(V_1 + V_f - V_s)}{KT_e}], \tag{1}$$

where I_{1es} and I_{1is} are electron saturation current and ion saturation current respectively; they pass through probe number one; also, e is electron charge, V_f is the floating potential, V_s is the probe sheath potential, T_e is electron

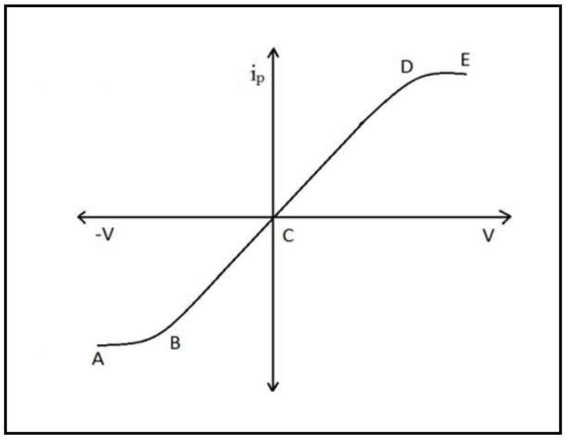

Figure 4. Characteristic I-V diagram for two fully symmetric probes.

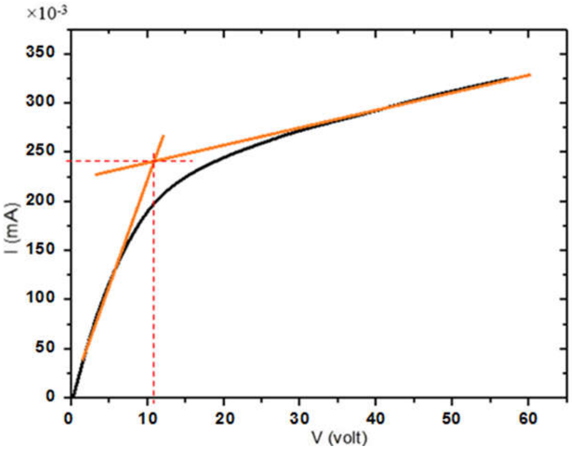

Figure 6. (color online) Characteristic I- V curve for typical argon and the way of drawing two tangent lines and the emerging junction point of coordinate (I, V).

temperature, and K is Boltzmann constant. More mathematical detailed formulas about the resultant ion saturation of the two probes can be easily found in the ref. [1]. Here, we have focused on measuring the mean value of electron temperature and the resultant saturation current from I-V diagrams. Therefore, by inserting two double Langmuir tips into the different place of the produced plasma, the characteristic I-V curve could obtained and depicted for seven different gases, as represented in figure 5. In our experimental method, as shown in figure 6, the vertical axis was the current driven from the probes in mA and the horizontal axis showed the voltage between probes tips for argon. As indicated in figure 6, the characteristic I-V curve has two tangent lines; one tangent is drawn at the point of inflection and the other one in the ion saturation current region; so the I-V coordinate of the junction point of these two tangent lines gives us information to calculate the plasma temperature. After measuring the average value of plasma temperature from the characteristic I-V curve, another important plasma parameter that should be obtained is electron density.

It should be mentioned thatthe electron and ion distribution function at the probe sheath edges are

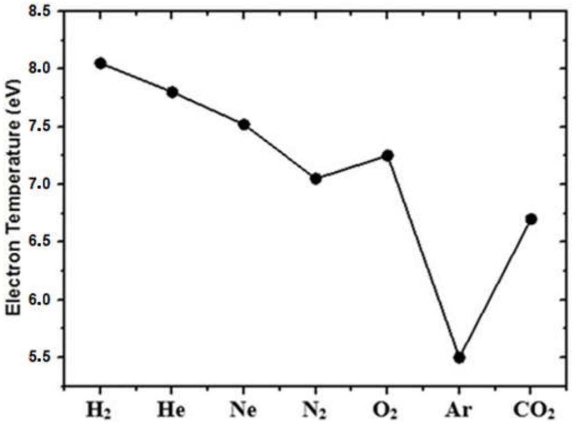

Figure 7. Maximum values of simulation results obtained for the electron temperature of seven different gases in eV.

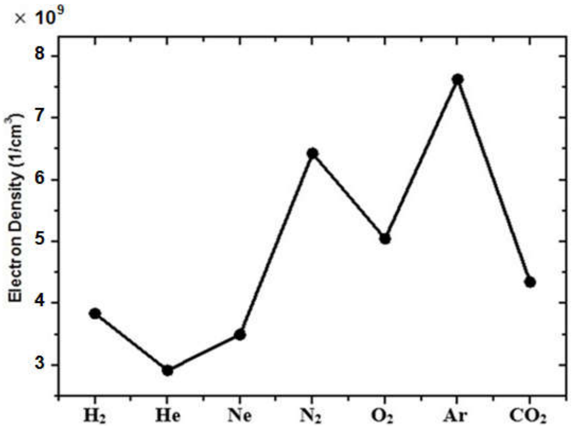

Figure 8 Maximum values of simulation results obtained for electron plasma density of seven different gases in cm^{-3}.

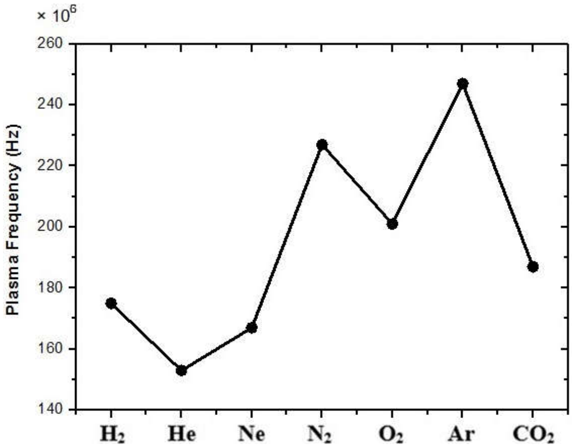

Figure 9. Maximum values of simulation results obtained for electron plasma density of seven different gases in Hz.

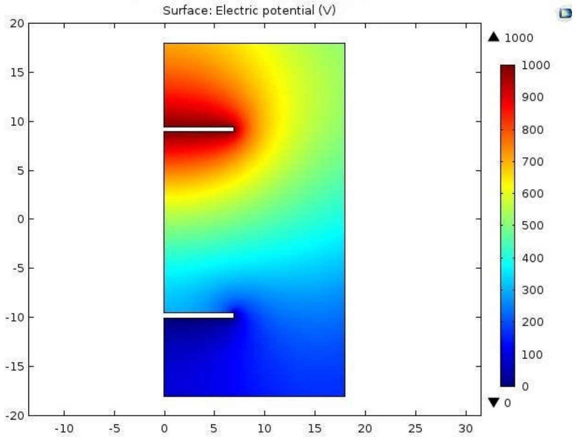

Figure 10. (color online) Electrical potential between anode and cathode.

considered to be Maxwellian, so that the most important requirement of pre-sheath and sheath transitions can be satisfied. Furthermore, the electrons and ions are assumed to penetrate the sheath region due to their large thermal velocities. After calculating plasma density, the electron frequency that entirely depends upon the plasma density is the fundamental property of the plasma and represents the frequency at which the electrons cloud oscillates with respect to the ion cloud; it can be obtained from the following relation, as shown in eq. (2)

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{m \times \varepsilon_0}} \Rightarrow f_{pe} = \omega_{pe} / 2\pi \,, \tag{2}$$

where m is electron mass and ε_0 is the vacuum electric permittivity.

3. Simulation method

Simulating the produced plasma originated from seven different gases performed by the COMSOL Multiphysics simulator in the plasma module using dc discharge interface. As an introduction to dc discharge theory, due to the complexity of coupling the electrostatic field to the transport of electrons and heavy species, the plasma module provided this multi physics interface specially designed for dc discharges [16]. The complicated coupling between the electron transport, heavy species transport, and electrostatic field could be handled automatically by the software [16]. In order to confirm our experimental results, we have done simulations by the COMSOL Multiphysics simulator. Our simulation results indicated the maximum values obtained for the plasma temperature, density and oscillation frequency for seven well- known gases, as depicted in figures. 7, 8 and 9, respectively. It could be deduced from the comparison between figures and the experimental results in table 1 that the experimental values were in a very good agreement with the simulations. After applying the real condition in this software, the electron temperature and density for 7 different gases were obtained. figure 10 indicates the electrical potential between anode and cathode. The simulation results for seven gases are depicted in figures. 11 to 17. In order to simulate plasma oscillations, we have drawn a line between the anode and cathode to calculate the plasma frequency on this line, which simulated plasma frequency as depicted in figure 18.

4. Results and disscution

In our measurements, we have used seven well known gases, Ar, He, Ne, N_2, O_2, CO_2 and H_2, in the constant discharge voltage of 1 kV and the constant pressure of 0.34 mbar. Experimental measurements showed that the

Table 1. Experimental values obtained for electron temperature mean value, density and plasma oscillation frequency.

Gas	H2	He	Ne	N2	O2	Ar	CO2
Density (cm^{-3})	1.761×10^9	1.318×10^9	1.45×10^9	3.288×10^9	2.238×10^9	3.542×10^9	1.923×10^9
Temperature (eV)	7.895	7.615	7.356	6.931	7.127	5.316	6.597
Frequency (Hz)	1.190×10^8	1.030×10^8	1.081×10^8	1.627×10^8	1.342×10^8	1.689×10^8	1.244×10^8

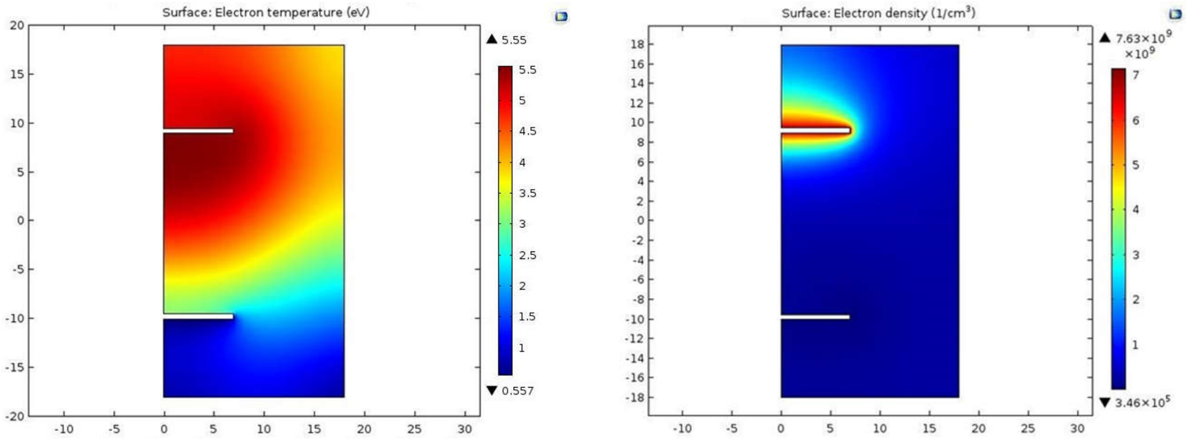

Figure 11. (color online) (left) Simulation of electron temperature for argon plasma (right) Simulation results of electron density for argon.

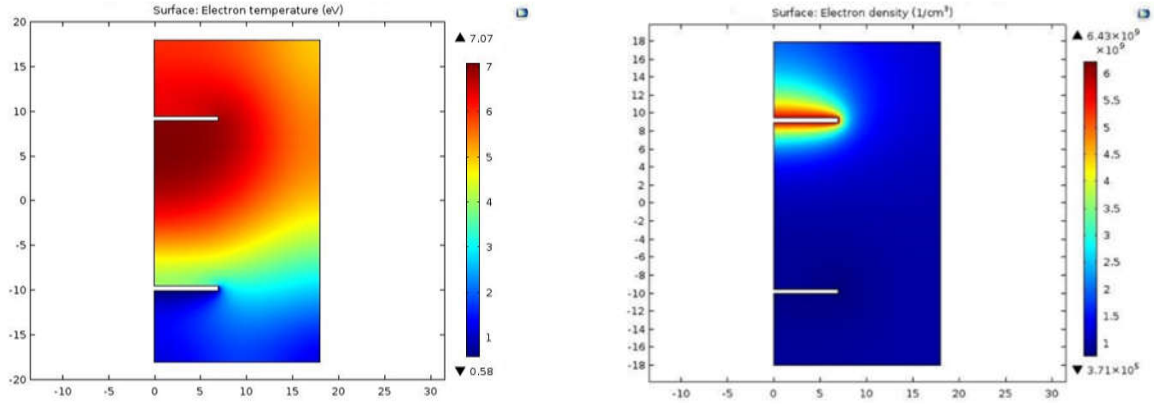

Figure 12. (color online) (left) Simulation of electron temperature for Nitrogen plasma (right) Simulation results of electron density for Nitrogen.

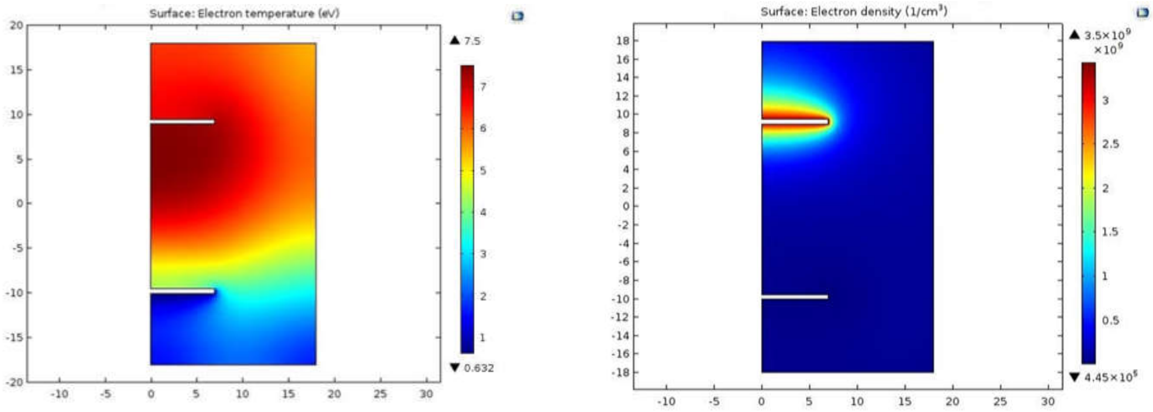

Figure 13. (color online) (left) Simulation of electron temperature for Neon plasma, (right) Simulation results of electron density for Neon.

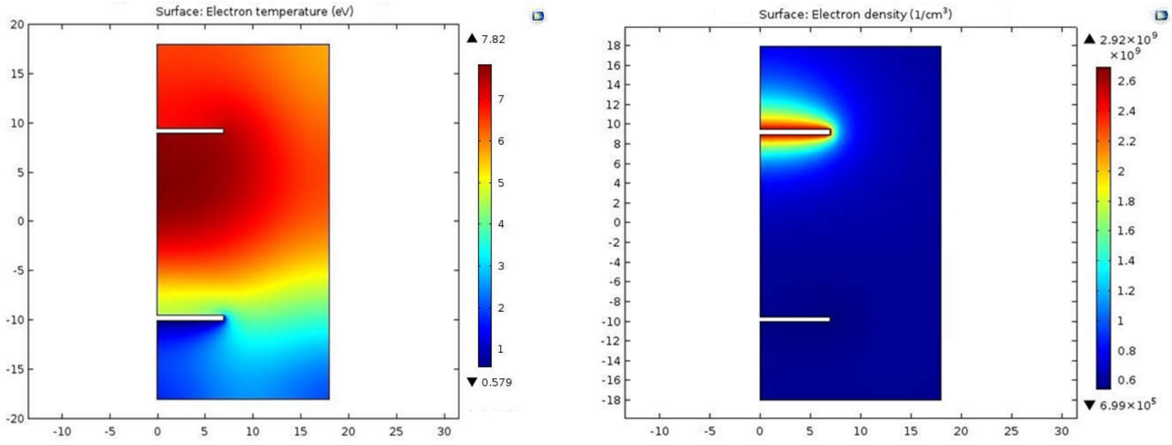

Figure 14. (color online) (left) Simulation of electron temperature for Helium plasma, (right) simulation results of electron density for Helium.

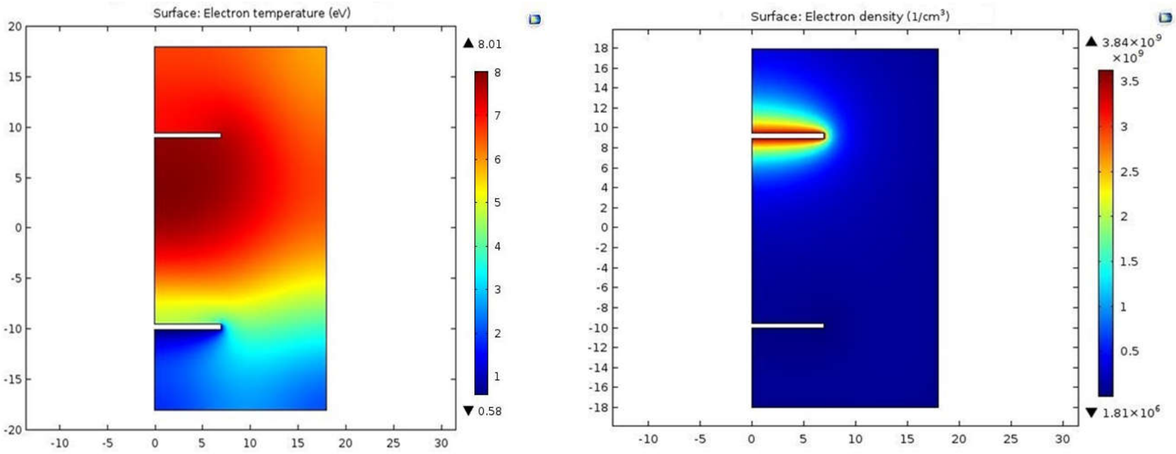

Figure 15. (color online) (left) Simulation of electron temperature for hydrogen plasma, (right) simulation results of electron density for hydrogen.

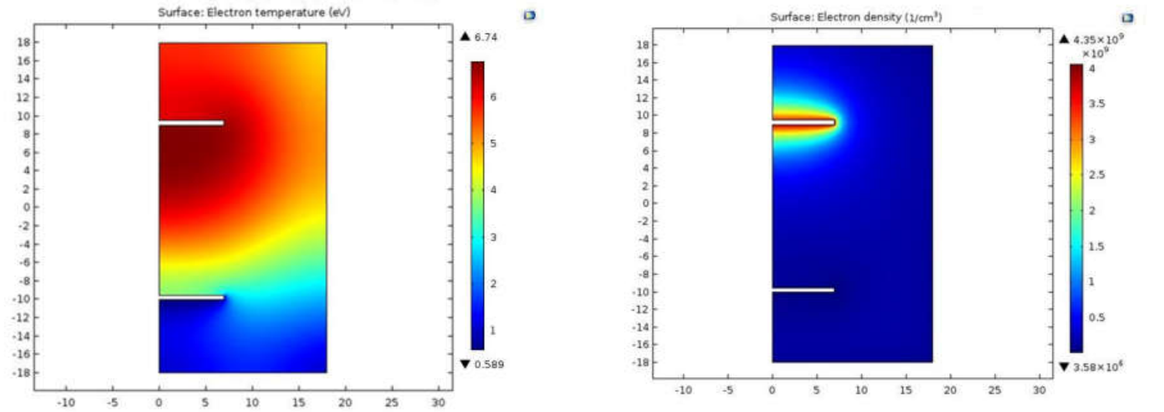

Figure 16. (color online) (left) Simulation of electron temperature for Carbon Dioxide plasma, (right) simulation results of electron density for Carbon Dioxide.

average value of the electron temperature of the produced plasma from seven different gases ranged from 5.316 to 7.895eV, such that the maximum temperature was for hydrogen molecules and the minimum belonged to argon. The results also indicated that the electron density of the generated plasma was about 1-3×10^9 cm^{-3} and plasma frequency ranged from 1-1.689×10^8 Hz. One of the main results was that the maximum plasma density belonged to argon with the highest plasma density 3.542×10^9 cm^{-3} and with the lowest temperature 5.316 eV. Moreover, our experiments reported that highest plasma frequency belonged to argon, and it was measured to be about 1.689×10^8 Hz. As shown by the experimental values in table 1, it H_2 had the highest

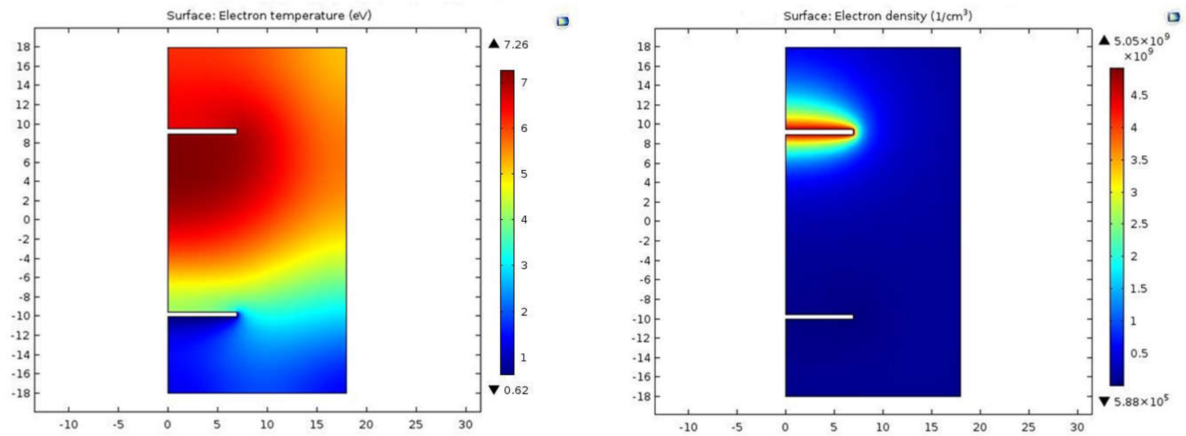

Figure 17. (color online) (left) Simulation of electron temperature for oxygen plasma, (right) Simulation results of electron density for oxygen .

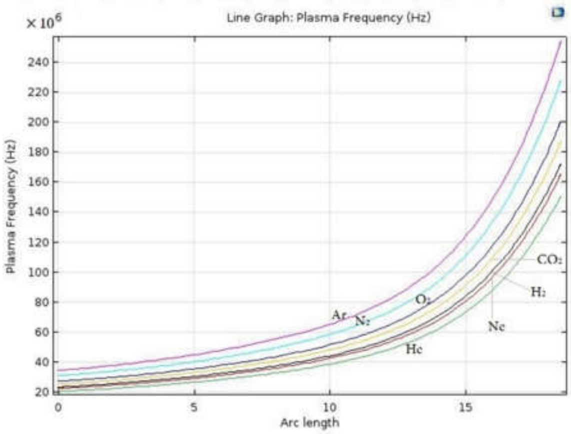

Figure 18. (color online) Simulation results of plasma frequency versus arc length.

temperature of 7.895 eV and the relatively low plasma frequency of 1.190×10^8 Hz. The electron density measured for Helium had the lowest value of 1.318×10^9 cm^{-3}. Another important result could be deduced from the I-V diagram. Figure 6 which shows that argons had the highest resultant saturated current, obviously leading to the highest electron density in between all other plasmas. Figures 11 to 17 indicate the simulation results of electron temperature and density for argon, nitrogen, neon, helium, hydrogen, carbon dioxide and oxygen , respectively. According to the plots, by referring to the maxima simulation values depicted in figures 7 to 9, it could be concluded that the simulations results were in agreement with the experimental data, with a good consistency; One can consider these simulations as a proper verification of the experimental data. figure 18 presents the variation of the plasma frequency with respect to the arc length. As shown in figure 18, by increasing the arc length, the distance between anode and cathode, the plasma oscillations were increased and the highest frequencies obtained for argon had a good consistency with the third column of the experimental data in table 1. The key is that both the increase in applied voltage across the electrodes and the pressure inside the discharge tube could increase the electron number density and plasma temperature [1]; These will be studied in the next work and published as soon as possible.

5. Conclusion

We have successfully measured the plasma parameters using a double Langmuir probe diagnostic in inhomogeneous, non- magnetized plasma environments. Experimental results indicated that electron temperature, electron density, and also electrons oscillation frequency could have different values for seven gases, but they were relatively close to each other. Furthermore, simulation results confirmed the experimental measured values of the plasma parameters with a good consistency. Meanwhile, the comparison between experimental data and COMSOL Multiphysics simulation results predicted that the Langmuir double probe diagnostic system could be a proper tool to measure the main plasma parameters. In our measurement, the most reliable results for electron density and temperature for argon plasma could be selected as the main result with the highest plasma density 3.542×10^9 cm^{-3} and the lowest temperature 5.316 eV, respectively. Meanwhile, between all seven gases, the densest plasma originated from the argon glow discharge and the highest temperature was for hydrogen plasma in such a model. Another interesting result related to the plasma produced from hydrogen discharge, with a density and temperature higher than those of Neon and Helium plasmas. The results also indicated that using the COMSOL Multiphysics simulator for simulating produced plasma could be a proper tool for such studies. Meanwhile, the valuable data from such studies could be widely used, with extensive applications in industries such as environment and medicine, surface treatment, biomedical sciences, pollution control, gas lasers, light source, chemical synthesis, MHD energy converters and fabrication of electronic circuitry [1, 3].

References

1. B Ghimire *et al.*, *Journal of science, Engineering and Technology* **10** (2014) 20.
2. A Bogaerts *et al.*, *Spectro Chimica Acta*, B **57** (2002) 609.
3. J Reece Roth, "*Industrial Plasma Engineering*", Institute of Physics Publishing, Bristol and Philadelphia (1995).
4. A Brockhaus *et al.*, *Plasma Sources Science and Technology*, **3** (1994) 4.
5. E O Johnson and L Malter, *Physical Review* **80** (1950) 58.
6. L S Pilling *et al.*, *Review of Scientific Instruments*, **74** (2003) 7.
7. F F Chen, "*Electric Probe Plasma Diagnostic Techniques*", Edited by Huddleston and Leonard, Academic Press, New York (1965).
8. S Mijovic *et al.*, *Publ. Astron. Obs. Belgrade* **84** (2008) 313.
9. D Akbar and S Bilikmen, *Chin. Phys. Lett*. **23** 5 (2006) 1234.
10. A K Shrestha *et al.*, "*Double Langmuir Probe for Plasma Parameters Measurement*", Proceedings of the International Conference on Plasma Science and Applications **10**, II (2014) 6.
11. J R Patterson *et al.*, "*A Langmuir Probe Diagnostic for Use in Inhomogeneous, Time-Varying Plasmas Produced by High-Energy Laser Ablation*", LLNL-CONF-554371, (2012) May 6, 2012 through May 10, (2012).
12. M B Hopkins, *J. Res. Natl. Inst. Stand. Technol.* **100**, 4 (1995) 415.
13. H Jin Yoon *et al.*, *Jpn. J. Appl. Phys*. **38**, 12 (1999) 6890.
14. S S Pradhan, *et al.*, *Journal of Physical Sciences* **10** (2006) 158.
15. T K Popov *et al.*, *Plasma Sources Sci. Technol*. **25** (2016) 033001.
16. "*COMSOL Multiphysics Reference Guide*", Protected by U.S. Patents (2012), 7, 519, 518; 7, 596, 474; and 7, 623, 991. COMSOL 4.3a.