Eco. Env. & Cons. 30 (4) : 2024; pp. (1965-1971)
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ISSN 0971–765X

DOI No.: http://doi.org/10.53550/EEC.2024.v30i04.082

Effect of Voltage and Electrode gap on cold plasma temperature

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(Received 4 August, 2024; Accepted 5 October, 2024)

ABSTRACT

The cold plasma reactor was fabricated and was used for the treatment of different lignocellulosic materials such as rice straw. The operating conditions of plasma were determined under the present study, the independent parameters being the DC plasma voltage, electrode gap and reactor pressure (vacuum), whereas the dependent parameters were the plasma temperature and time. The three levels of plasma temperatures obtained and residence times selected were 110, 117 and 128 and 30, 60 and 120 min, respectively. The increase in plasma voltage resulted in increase of plasma temperature whereas reduction in electrode gap increased the plasma temperature. The above obtained parameters will be used for the treatment of lignocellulosic materials and would be environment friendly and non-toxic in nature.

Key words*: Cold plasma, electrode gap, reactor pressure, plasma temperature, plasma voltage*

Introduction

The concept of plasma emerged in 1879, given by William Crooks, and it was defined as the fourth state of matter (Kalia *et al*., 2013). Plasma is a partially or fully ionised gas, made up of electrons, ions, excited and non-excited molecules, reactive species, and photons (Jiang *et al*., 2014). It can be further classified into two types on the basis of temperature. Thermal plasma, which has the temperature lying above 3000 K and the low temperature plasma or the cold plasma or the non-thermal plasma, in which the temperature lies close to room temperature (Gao *et al*., 2018). Therefore, thermal plasma is not feasible in terms of reactor fabrication pertaining to high temperature operating ranges and higher energy consumption requirements, the experiments are advised to be conducted using the cold plasma technique. Recently, few experiments have been conducted for the pre-treatment of ligno-cellulosic materials using non-thermal plasma (Miranda *et al*., 2020; Ravindran *et al*., 2019). Kalia *et al*., 2013 reported that it was Irving Langmuir, an American chemist, who introduced the term "plasma" in 1928 to describe this particular state of matter. Langmuir's work was instrumental in formalizing the understanding of plasma and its distinct properties. He expanded upon Crookes' observations and conducted extensive research on the behavior of ionized gases, contributing significantly to the scientific understanding of plasma. Since Langmuir's introduction of the term, plasma has become a well-recognized state of matter.

Plasma is now a subject of study in various scientific disciplines, including physics, chemistry, and engineering, and it has diverse applications ranging from plasma physics research to industrial processes. Jiang *et al.,* (2014) highlighted that plasma is a remarkably versatile and distinct medium that holds the capability to modify the surfaces of plant fibers in a unique manner. The special properties of plasma, such as its reactivity and the ability to contain both charged and neutral species, make it an intriguing and potent tool for surface modification. It is harnessed for various applications, including treating plant fibers, due to its potential to induce surface chemical changes, enhance adhesion, and even introduce new functionalities. Wu *et al.*, (2013) explained that non-thermal plasma indeed involves partial electrical discharges that lead to unique conditions where the electron temperature is much higher than the temperature of the surrounding gas molecules. Because of these energetic particles, NTP is capable of initiating and accelerating chemical reactions that might not occur under normal thermal conditions. The increased energy of these particles contributes to breaking chemical bonds, ionizing molecules, and generating reactive species that play a significant role in various applications, including surface modification, sterilization, pollutant degradation, and material synthesis. Hayashi *et al.,* 2000 highlighted that non-thermal plasma has the potential to serve as a preliminary treatment method for biomass, with its primary application being the modification of lignin for lignocellulosic materials. This process allows for the isolation of individual components including lignin, cellulose, and hemicellulose, each of which holds intrinsic value for further utilization. Lignin, for instance, can be transformed into commercially valuable products such as activated carbon and vanillin, a compound used in the synthesis of herbicides, antifoaming agents, and antimicrobial agents.

Grbic *et al.,* (2022) mentioned that Lignocellulosic biomass, an economical raw material, holds significant potential for biofuel and biogas production through fermentation, owing to its rich carbohydrate content. Emerging as an environmentally friendly and sustainable alternative, advanced oxidation techniques offer promising solutions. Termed "green" treatments, these processes generate reactive species to target cellulose, hemicellulose, and lignin components. Lim and Zulkifli, (2018) studied the impact of non-thermal plasma (NTP) treatment on pulverized palm-based empty fruit bunches (EFB) biomass. The outcomes emphasize the capability of NTP treatment to modify the surface attributes of empty fruit bunches, enhancing their conversion and processing efficiencies by augmenting surface reactivity.

Meoli *et al.,* (2023) highlighted that, in the face of climate change and a growing global population, the need for innovative solutions that can generate biochemical through environmentally sustainable methods has become paramount. Recently, considerable scientific attention has been directed towards non-thermal plasma, an innovative and eco-friendly treatment method that exhibits the potential to achieve high concentrations of fermentable sugars. Non-thermal plasma offers advantages such as cost-effectiveness and the absence of waste generation, optimal configuration of the plasma reactor is crucial to curtail time and energy requirements. Therefore, the present study was carried out for the optimization of the plasma treatment conditions, so that further biomass could be treated under the obtained set of conditions.

Material and Methods

The generation of plasma was done under controlled high vacuum environment, high voltage low current DC power supply, variable electrode gap under the effect of magnetron based plasma cathode gun with carrier gas as Lab grade pure nitrogen. The experimental plan for the determination of the levels of the plasma temperature is represented in Table 1.

Plasma chamber

The plasma chamber is made up of Stainless Steel (SS-304) as shown in Figure 1. The internal diameter is 210 mm and its height being 200 mm. It has 265 mm flanges on top and on the bottom side of the

Table 1. Experimental parameters for determination of temperature levels

Sl. No.	Independent Parameters	Levels	Dependent Parameter
1.	V- Plasma Voltage (V)	3 (400, 450 and 500)	Temperature (°C)
2.	G- Electrode gap (mm)	3 (35, 40 and 45)	
3.	P- Reactor pressure (mbar)	3 (0.06, 0.05 and 0.04)	

Fig. 1. Plasma chamber

chamber. The top flange has provision for mounting the plasma gun assembly and the bottom flange has KF-25 port for attaching further peripherals as per varying experimental requirements. The plasma chamber was fitted with a 7.62 cm diameter glass window, present (Figure 2). Experimental conditions can be monitored occurring inside the reactor through the window.

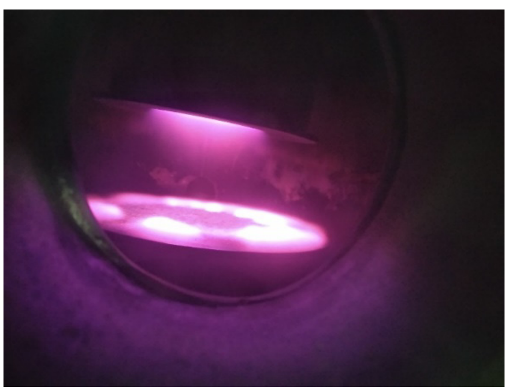

Fig. 2. Plasma reactor viewing glass window

Electrodes

The sample holder, kept at the bottom of the reactor (Figure 3) acts as the anode and is connected to the ground terminals of the direct current (DC) power supply system. The sample to be treated is kept on the sample holder, by opening the reactor and then retightening was done, after placing the sample.

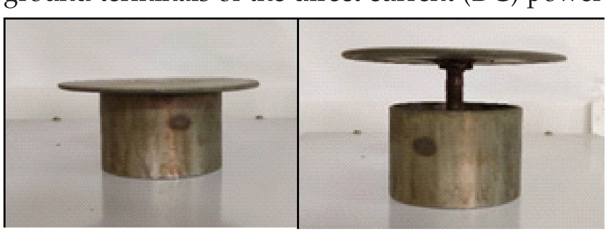

Fig. 3. Adjustable sample holder present in the plasma chamber

Direct current (DC) plasma high voltage power supply

The plasma gun is connected to the high voltage DC power supply (1000 V) with digital voltage and current indicator, and it supplies the electrical energy needed for creating plasma. The DC power can be varied from 0 to 1000 V with the help of voltage regulator, already on the DC power supply panel as shown in Figure 4.

Fig. 4. High voltage DC power supply system

Vacuum Rotary pump (RP)

The rotary pump (Figure 5) is used to create lower levels of vacuum in the reactor, has a power consumption of about 550 Watts, revolves at 1425 RPMs, has 1-1.5 l of vacuum pump oil (HLP-68) inside it and needs replacement periodically after about 100 hours of experimental runs.

Fig. 5. Rotary vacuum pump

Pirani gauge

The vacuum pressure is indicated on the pirani gauge, which is used to measure lower vacuum levels (Figure 6). Change of pressure in vacuum system brings about a rise or fall in number of gas molecules present and hence a rise or fall in the thermal conductivity of the gas. Thus, the heat loss of constant voltage electrically heated filament in the system varies with the pressure. The pirani gauge head filament has high temperature co-efficient of resistance. So a slight change in system pressure brings about useful change in filament resistance resulting in an out of balance voltage which can be read as a pressure on the meter.

Fig. 6. Pirani gauge for lower vacuum measurement

Generation of plasmonic radicals

Plasma voltage

Plasma voltage is the direct current (DC) voltage supplied to the electrodes in volts, by the high voltage DC power supply system for the formation of plasma with a least count of 1 V. The higher the available voltage, greater electrode gap distance can be jumped for the plasma formation. Plasma voltage was set using the rotating knob type regulator available on the power supply system and the real time voltage readings can be seen on the digital indicator, present on the front panel of the power supply system. The three levels of voltage selected for the present study was 400 V, 450 V and 500 V and was represented by V1, V2 and V3, respectively.

Reactor pressure

The reactor pressure is the vacuum level of the plasma chamber or reactor, at which the experiment is intended to be performed, measured in mbar with its least count being as 0.01 mbar. Vacuum level is raised using the rotary pump, which evacuates the gases out of the reactor and is lowered by using the needle valve, which allows the pure nitrogen gas to flow into the reactor. The real time vacuum levels are read on the pirani meter simultaneously while operating the needle valve. In the present study, air was first evacuated from the reactor using the rotary pump and then again pure lab grade nitrogen gas (99.99%) (Figure 7) was supplied to the reactor till the reactor reached the atmospheric pressure, which was again evacuated until the desired reactor pressure levels were obtained. The desired vacuum level was maintained by operating the needle valve precisely. Air was evacuated in order to ensure the experiments were carried out in pure nitrogen environment, free of undesirable foreign gases or water vapour present in the air. Lower levels of vacuum in the reactor causes sparks, which can lead to short circuits and damage the power supply system and at high levels of vacuum, for a certain voltage and electrode gap, the plasma glows off. Thus, an optimum level of vacuum is necessary for plasma to be stable. The three levels of reactor pressure selected for the present study was 0.06 mbar, 0.05 mbar and 0.04 mbar and was represented by P1, P2 and P3, respectively.

Fig. 7. Nitrogen gas cylinder and its regulator system

Electrode gap

Electrode gap is the distance between the cathode and the anode, and was measured in mm with the help of a linear scale with least count of 1 mm. The plasma gun can be moved up or down and then fixed at the desired position as per the electrode gap requirement of the user. The three levels of electrode gap selected for the present study was 35 mm, 40 mm and 45 mm and was represented by G1, G2 and G3, respectively.

Results and Discussion

Plasma Temperature

A K-type thermocouple was installed inside the reactor for the plasma temperature measurement. The readings for plasma temperature (°C) can be seen on a digital display cum microprocessor circuit, connected to the thermocouple probe. The thermocouple tip was placed at the center of the plasma, just above (about 2 mm) the sample holder, inside the reactor (Figure 8). The sample holder was fabricated and mounted on an adjustable stand, so that height of the sample holder can be adjusted as per experimental requirements. The thermocouple probe was inserted into the reactor through a KF-25 port, at the side of the plasma chamber. The displayed temperature readings were noted down in an excel sheet, corresponding to each of the treatments and further analysis and interpretations was carried out. The best three plasma temperatures(°C) were obtained from the experiments performed, and the corresponding parameters (Plasma Voltage, Reactor Pressure and Electrode Gap) were noted. Further experiments of performing plasma treatment to the samples were carried out at the three best levels of temperature denoted as T1, T2 and T3.

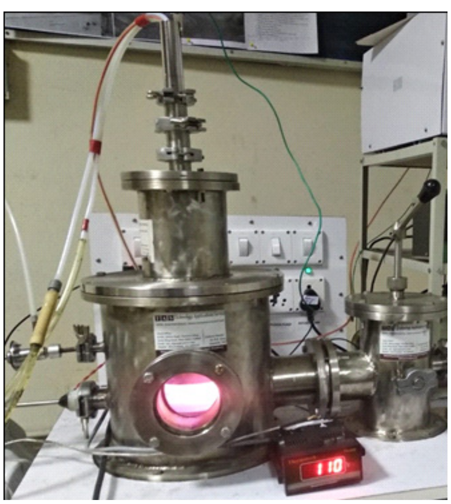

Fig. 8. K type thermocouple mounted in the chamber

The three levels of voltage (V1, V2, V3) was 400, 450 and 500 V and three levels of electrode gap (G1, G2, G3) was 35, 40 and 45 mm. The plasma temperature was measured and it was found that the best three levels of temperature was found at V1G1, V2G1 and V3G1. It was found that as the gap between the electrodes was increased, the plasma temperature reduced and shows inverse relationship. With increase in voltage, the plasma temperature increased and indicates direct relationship. Reactor pressure showed negligible effect on plasma temperature at the three selected levels. The temperature conditions finally selected was found to be 110, 117 and 128 °C as shown in Figure 9 and further the biomass would be treated under the obtained conditions and the effect of cold plasma on biomass would be analysed.

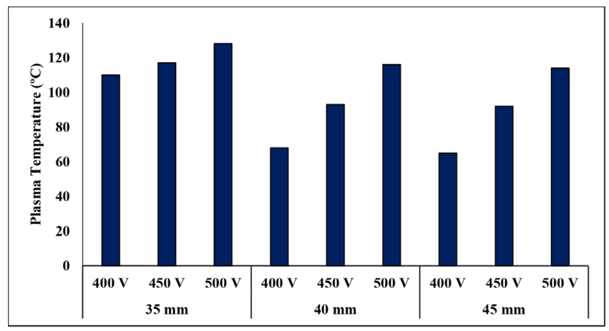

Fig. 9. Variation of plasma temperature with Plasma voltage and Electrode Gap

Correlation between parameters

The R^2 value of 0.89 for the relationship between supply power and plasma temperature indicates that approximately 89% of the variation in supply power, shown in Fig. 10 can be explained by changes in plasma temperature, demonstrating a strong linear relationship. Similarly, the R^2 value of 0.85 between supply current and plasma temperature shows that around 85% of the variation in supply current is influenced by plasma temperature, highlighting another strong dependence. In contrast, the R^2 value of 0.46 for plasma current versus plasma temperature suggests that only 46% of the variation in plasma current is explained by plasma temperature, indicating a weaker and less consistent relationship. Lastly, the near-perfect R^2 value of 0.99 for the relationship between supply current and supply power signifies a very strong linear dependence, meaning changes in supply power almost entirely dictate the variation in supply current.

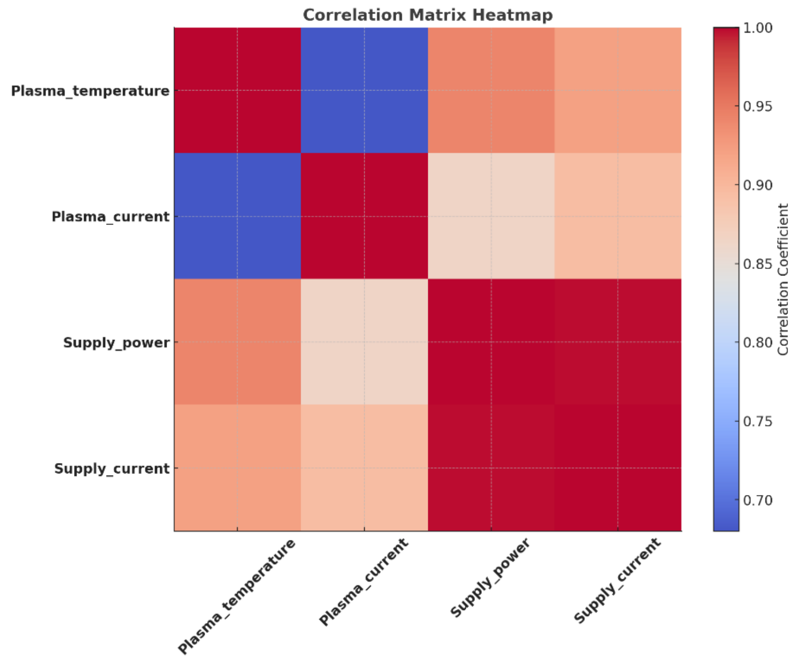

Fig. 10. Correlation between different plasma generation parameters

Conclusion

The cold plasma reactor was fabricated and can be used for the treatment of different lignocellulosic materials such as rice straw. The operating conditions of plasma were determined under the present study, the independent parameters being the DC plasma voltage, electrode gap and reactor pressure (vacuum), whereas the dependent parameters were the plasma temperature and time. The three levels of plasma temperatures obtained and residence times selected were 110, 117 and 128 ^{o}C and 30, 60 and 120 min, respectively. The increase in plasma voltage resulted in increase of plasma temperature whereas reduction in electrode gap increased the plasma temperature. The above obtained parameters will be used for the treatment of lignocellulosic materials and would be environment friendly and non-toxic in nature.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors are sincerely thankful to Director (ICAR-CIAE, Bhopal); Dean (IARI, New Delhi) and Head (AEP-CIAE); for their support and encouragement in terms of providing facilities and materials. Sincere gratitude is extended to all staff of Agricultural Energy and Power (AEP) division, ICAR-CIAE, Bhopal for their help.

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