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Characterization of Cold Plasma with Glow Discharge Mechanism of Plasma Jet System

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Abstract*-Cold plasma with glow discharge mechanism exhibiting a uniform ionization process when a background gas passes through the discharge region of the plasma reactor under a certain optimum configuration of input parameters. A glow discharge is a homogeneous and effective mechanism of cold plasma for industrial applications due to the continuous and stable discharge process compared to the filamentary discharge. Meanwhile, the development of glow discharge plasma operated under atmospheric pressure condition is indispensable to overcome the weaknesses of filamentary discharge plasma, such as the non-uniform and discontinuous discharge process. The discharge mechanism is essentially dependent upon the input parameters of the plasma system, such as the amplitude of the voltage supply, the operating frequency, and the flow rate of the background gas. In this paper, the effects of voltage supply on plasma discharge characteristics produced from the plasma jet reactor with the high-voltage electrode are discussed. The value of voltage supply is tuned to be suitable with the discharge gap, frequency supply, and background gas flow rate in producing the homogeneous glow plasma discharge. The characteristics of the glow plasma discharge produced are analyzed based on the pattern of the charge-voltage Lissajous figure and time-domain discharge current techniques. Results show that the most efficient and uniform plasma is disclosed by the configuration of input parameters such as 0.5 kV of supply voltage, 20 kHz of operating frequency, and 0.8 L/min of purified helium gas flow rate. The parallelogram-like Lissajous figure obtained indicating the homogeneous plasma discharge with a constant value of discharge capacitance.

Keywords—Atmospheric pressure plasma; plasma jet; cold plasma; glow plasma discharge.

I. INTRODUCTION

Plasma is a state of matter that providing an ionization process through an electrical discharge mechanism, which ionized the working gas at different ionization levels. The level of ionization energy is different based on the identities of working gas. Thus, the electrical energy required to initiate the discharge process is non-identical for each discharge gas. Besides, the mechanism and condition of plasma discharge were also affected by few factors such as the value of voltage supply, frequency supply, the geometrical structure of plasma reactor, type, and rate flow of working gas [1]. All the factors related to the plasma discharge mechanism need to be considered at the optimum condition to produce the expected mechanism of plasma discharge.

The discharge mechanism of cold plasma can be categorized into two states which are filamentary and glow discharges. Filamentary discharge is a state of plasma discharge that exhibits non-uniform or non-homogenous discharge condition [2] [3]. Meanwhile, glow discharge is a state of cold plasma that is formed through uniform and homogenous discharge of background gas [2] [4]. Cold or non-thermal plasma can be produced under two pressure conditions: low and atmospheric pressure conditions.

In this paper, the applied voltage characteristics for producing the glow plasma discharge were determined and optimized. The applied voltage amplitude was manipulated, whereas the voltage frequency and discharge gas flow rate were fixed to characterize the mechanism of plasma discharge produced. The type of discharge gas was retained with purified helium gas. Besides, the configuration and geometrical structure of the plasma jet reactor also remain unchanged.

According to the shaped and geometrical structure of the plasma reactor designed in this study, it is required to determine the optimum working parameter, especially the voltage supply value. The properties of plasma discharge were determined according to the characteristics of the voltage-current plot and charge-voltage of the Lissajous figure.

The most optimal and effective input parameters to form a plasma with a glow discharge mechanism were also identified and discussed comprehensively in this paper. Therefore, the challenge is to research and find the optimum values of the voltage supply experimentally, which only applied to the designed plasma jet reactor with its unique geometry.

II. METHODOLOGY

A. Structure of Plasma Reactor

The structure of the plasma reactor is a crucial part of producing the homogeneous glow plasma. The plasma reactor needs to have the capability to produce plasma discharge under the optimum condition of input parameters. A plasma jet reactor

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was designed, as shown in Fig. 1, to generate gas-volume discharge due to the superiority of the structure.

The discharge gap was maintained at 0.7 cm, in which the ground terminal was covered by a capillary tube with 2.0 cm of outer diameter and 0.15 cm of thickness. The position of the ground ring was placed 1.5 cm from the bottom tip of the capillary tube.

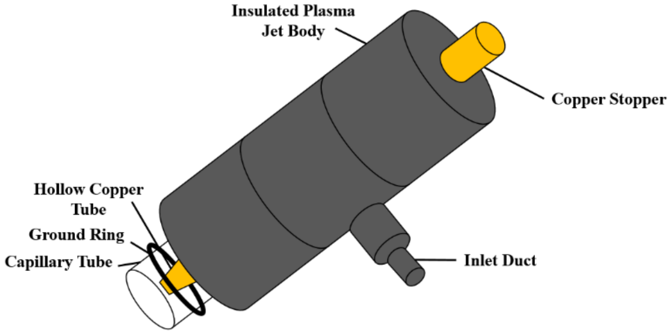

Fig. 1. The geometrical structure of plasma jet reactor.

B. Experimental Setup

Fig. 2 shows the experimental setup of the cold plasma jet system.

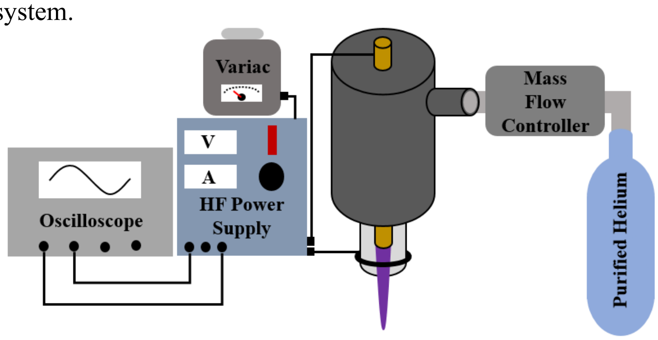

Fig. 2. Experimental setup of the cold plasma jet system.

Purified helium has been used as a discharge gas due to the benefits of its properties such as single element (monatomic gas), non-toxic, inert, odorless, and stable ionization state [5]. Since helium is a very good discharge gas with its lowest electron affinity, it might easily release the electron and accelerate the discharge process. The flow rate of discharge gas is fixed to 0.8 L/min to maintain the amount of helium molecules in the discharge process.

The plasma discharge was generated by applying AC high voltage supply. The voltage supply value is controlled using a single-phase voltage regulator from 0.5 kV to 3.0 kV in the step of 0.5 kV. In contrast, the frequency supply remains unchanged with 20 kHz of oscillation rate.

Two current types were measured to identify the mechanism of plasma discharge, which is resistive current, ***Ir*** and capacitive current, ***Ic***. The resistive current was observed to determine the discharge current, and the capacitive current was recorded to analyze the amount of charge produced from the discharge process.

C. Methods of Analysis

i. Typical Voltage-Current Waveforms

Generally, the voltage and current waveforms are used to characterize the plasma discharge. The time-domain analysis is a useful method to determine the properties of plasma discharge generated, such as frequency of supply, the amplitude of voltage and discharge current. In addition, the type of plasma discharge can also be identified based on the number and type of peaks of discharge current.

ii. Lissajous Figure

Lissajous figure or Bowditch curve is an infinite variety of curves formed by combining two waveforms having the same period [6]. In detail, the Lissajous curve is utilized to formulate the properties of plasma discharge. In the electrical theory of ozonizers, a classical Q – V loop with quasi-parallelogram shape signifying the plot of the ozonizer that exhilarated by an AC power source, typically a volume-discharge Lissajous figure is shown in Fig. 3 [7].

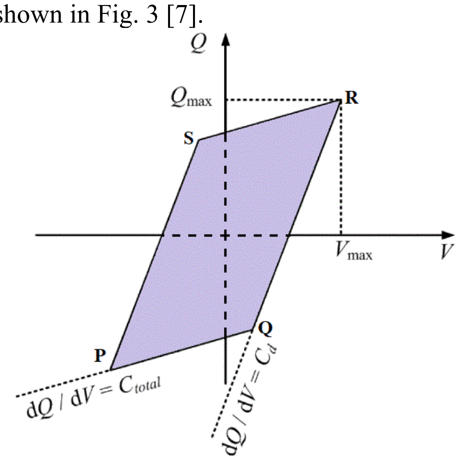

Fig. 3. Graphical presentation of classical Q – V Lissajous figure of volume–discharge ozonizer excited by sinusoidal voltage source [7].

III. RESULTS AND DISCUSSIONS

i. Voltage-Current Characteristics

Fig. 4 shows the voltage-current waveforms of plasma discharge under the different value of applied voltage. Significantly, the characteristics of the discharge current formed are affected by the value of applied voltage. The number of peaks of the discharge current increases as the voltage amplitude is raised.

Theoretically, plasma formation with a filamentary discharge mechanism consists of multiple pulses of discharge current for every complete cycle of supply voltage [7]. Meanwhile, the glow plasma is a mechanism of discharge that formed with the pulseless or single pulses of discharge current for every complete cycle [7].

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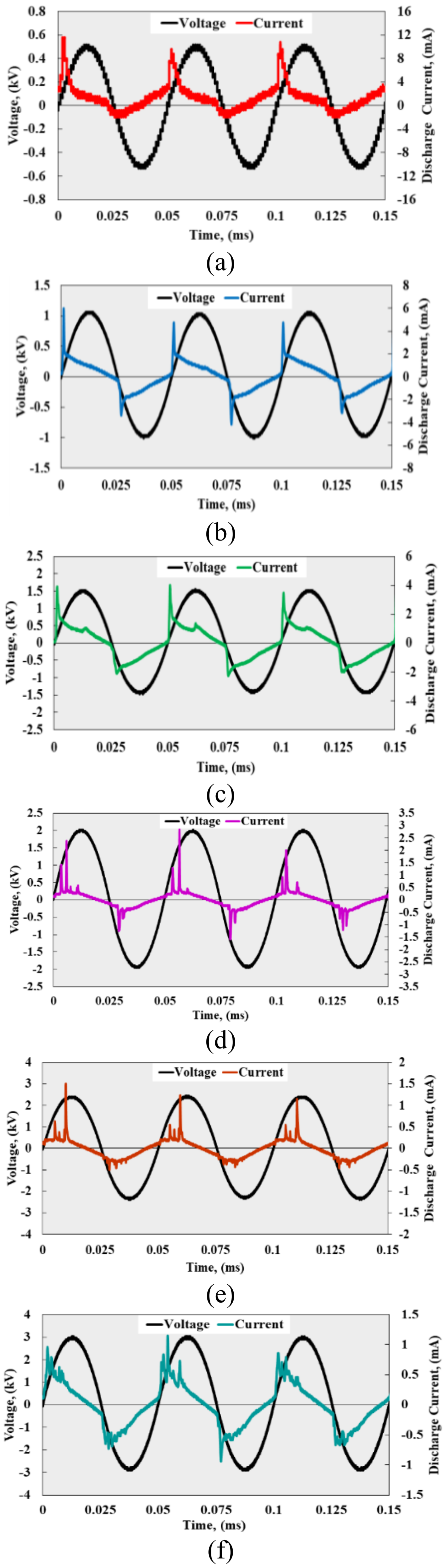

Fig. 4. Characteristics of voltage-current waveforms for plasma discharge under (a) 0.5 kV, (b) 1.0 kV, (c) 1.5 kV, (d) 2.0 kV, (e) 2.5 kV, and (f) 3.0 kV of applied voltage.

The discharge current has produced more than one peak as the voltage value increased to 1.5 kV. The number of peaks of discharge current continues to increase as the value of applied voltage is increased to 2.0 kV, 2.5 kV, and 3.0 kV. The plasma plumes produced at 0.5 kV and 1.0 kV of applied voltage are considered as a glow discharge such that the discharge current formed only a single pulse for each half cycle. The single pulse of the discharge current is consistently occurred for every cycle of the voltage supply, indicating that the process of glow discharge is stable in terms of discharge mechanism.

Molecules of helium gas considered among the molecules that required the lowest energy to discharge compared to others gas due to the weakest attractive force towards the electron valence [8] [9]. This triggered the molecule to release the electron on the outermost shell easily to form a free radical ion through an ionization process [10] [11]. Adequate ionization energy from the electric field formed in between two potential differences. Thus, the electron is knocked out from its valence orbital to form a free electron due to the collision of the liberated electron and the helium molecule [12].

At 0.5 kV and 1.0 kV voltages, only the helium molecules contained in the discharge chamber experience the process of discharge. Meanwhile, the natural gas molecules that are also contained in the discharge chamber do not experience a direct discharge process as they might require higher ionization energy [13] [14] [15]. Generally, glow discharge occurs at very low current and can be due to the recombination process of electron and hole which releases photons. The photoionization emits light, so it is a glow process.

The scenario turned to a different condition as the voltage further increased. The discharge no longer occurs on helium molecules only. In fact, the others natural gas molecules also experienced discharge process coarsely cause multiple peaks of discharge current are formed thereby indicating the mechanism of discharge has become unstable and happened heterogeneously [7].

ii. Lissajous Figure Analysis

Typically, the shape of Q – V loops also represents the mechanism of plasma discharge, as criticized in some literature [6]. Fig. 5 shows the Q – V Lissajous figure of plasma jet discharge under different values of applied voltage. The designed plasma jet chamber has considered matching the source parameters due to the Q - V curve showing a closed loop structure.

At the voltage of 0.5 kV, the corresponding Q – V Lissajous figure depicts a quasi-parallelogram shape, commonly found in the studies of homogenous and uniform discharge plasma. In the literature, the quasi-parallelogram shape of the Q – V loop was obtained by the glow discharge plasma, which was different from the quasi-almond shape of the Q – V loop derived from filamentary discharge plasma [7].

The shape of Q – V curves of plasma discharge under 1.0 kV and 1.5 kV shows an almost quasi-parallelogram shape. In some literature, the semi-quasi-parallelogram shape of Lissajous figure can also be considered a glow discharge [7]. Generally, the Q - V curve shape like this is formed when the magnitude of the first peak of discharge current showed the

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highest value compared to the next order of peaks [7]. The Q - V loops of plasma discharge tend to become almond-like shape under 2.0 kV, 2.5 kV, and 3.0 kV of applied voltage, representing the mechanism of unstable plasma discharge [7]. The horizontal and vertical inclined sides show a non-linear slope indicating the inconsistency of capacitance of the discharge process [7].

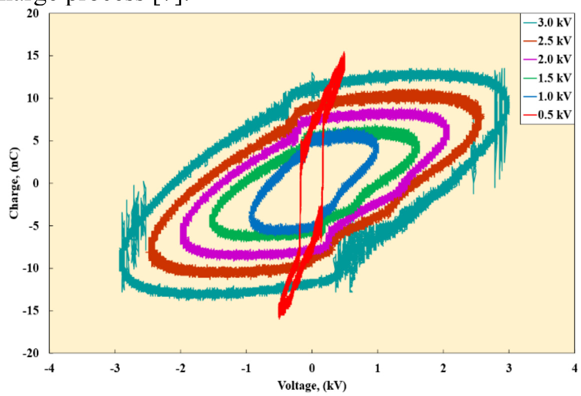

Fig. 5. The Q – V Lissajous figure of plasma jet discharge under the different voltage value.

Relatively, it is found that the quasi-parallelogram Lissajous figure has a longer side of horizontal-inclined (i.e. *PQ*) compared to the side of vertical-inclined (i.e. *QR*). This kind of typical discharge pattern indicating the homogeneity of the discharge process. Specifically, a uniform volume of discharge would form a parallelogram-like Lissajous figure because the discharge process might start and stop with a constant geometrical plasma shape (i.e. plume-like plasma) over a gas flowing gap. Besides, the parallelogram-like Lissajous figure also displays a constant value of discharge capacitance defined by a unique value of dQ/dV from the horizontal and vertical-inclined side of the parallelogram. In addition, a consistent single pulse of discharge current is also one factor contributing to the uniform plasma discharge, as shown by the parallelogram-like Lissajous figure.

IV. CONCLUSION

The mechanism of plasma discharge is a characteristic of an ionization process that exhibits the uniformity of the process. Literally, the characteristic of discharge can be identified according to the analysis of discharge current and charge-voltage loops of the Lissajous figure. The current of homogeneous volume-discharge can be categorized into two types; a single peak current and multiple peaks current with the first peak were the major components. Whilst, the current of heterogeneous surface-discharge consists of multiple peaks of discharge current, in which the first peak is not the major component. The analysis of the discharge mechanism based on the Lissajous figure shows that the uniform ionization process formed a parallelogram-like shape. On the contrary, the Lissajous figure of filamentary discharge was like an almond shape. The value of voltage has significantly affected the character of the plasma discharge, where the most effective and efficient plasma was produced at 0.5 kV of AC voltage supply, which is adequate and efficient enough to translate the energy supply by ionizing the molecules of monoatomic gas evenly.

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