Voltage-Current Effects on Medical Ozone and Specific Energy in Aluminum Mesh Double Dielectric Discharges

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Publication Date: 2026/06/17

Abstract: This study investigates the effect of voltage-current characteristics on medical ozone production and apparent specific energy input in a Double Dielectric Barrier Discharge plasma generator using aluminum mesh electrodes. The experiments were conducted by varying the operating voltage from 0.5 to 3.3 kV and the oxygen flow rate from 0.2 to 0.8 L/min. The results indicate that the voltage-current (V-I) characteristics and power consumption follow a strong quadratic increasing trend, signifying the onset of stable filamentary microdischarges upon exceeding the breakdown voltage. The highest ozone concentration, approximately 1.32 g/L, was obtained at the lowest oxygen flow rate of 0.2 L/min because the gas molecules remained longer in the plasma region. In contrast, the maximum ozone production capacity, approximately 0.51 g/min, was achieved at the highest flow rate of 0.8 L/min, indicating that gas throughput strongly affects the total ozone mass produced per unit time. Furthermore, SEI_{app} analysis revealed that higher gas flow rates significantly enhanced energy efficiency, thereby mitigating thermal dissipation-induced inefficiencies within the reactor. The DDBD configuration with aluminum mesh electrodes proved effective in generating stable and controlled ozone doses, making it a promising technology for medical ozone applications.

Keywords: *Double Dielectric Barrier Discharge, Aluminum Mesh Electrode, Ozone Concentration, Ozone Production Capacity, Apparent Specific Energy Input, Medical Ozone.*

How to Cite: Dodi Mariadi; Rodlatul Salmah1,4; Azizah; Eko Yulianto; Eva Sasmita; Sri Pujiyanto; Muhammad Nur (2026) Voltage-Current Effects on Medical Ozone and Specific Energy in Aluminum Mesh Double Dielectric Discharges. *International Journal of Innovative Science and Research Technology*, 11(6), 416-424. https://doi.org/10.38124/ijisrt/26jun564

I. INTRODUCTION

Ozone is a highly reactive oxidizing agent and has been widely recognized for its antimicrobial effectiveness against various pathogens, including bacteria, viruses, and fungi [1] [2]. Over the past few decades, medical ozone has rapidly evolved as a disinfecting and therapeutic agent. This growth is driven by the demand for residue-free sterilization methods, as ozone spontaneously decomposes into molecular oxygen [1] [2]. Its medical applications cover a wide range of clinical indications, from diabetic wound healing to systemic therapy through autohemotherapy [2]. However, the use of ozone in medical settings requires very strict dose control, as inaccurate dosage may lead to clinical ineffectiveness or unwanted oxidative risks for patients [2] [3].

Double Dielectric Barrier Discharge technology has emerged as one of the most effective methods for producing medical ozone because it can operate at atmospheric pressure with high stability and relatively low temperature [4] [5] [6]. Unlike conventional DBD systems, the DDBD configuration uses two dielectric barriers that isolate the gas flow from direct contact with the electrodes, thereby minimizing metal contamination and producing ozone with a high level of purity suitable for medical standards [5] [6]. Previous studies have shown that reactor performance strongly depends on operating parameters such as voltage, gas flow rate, and electrode geometry configuration [4] [6] [7]. Nevertheless, ozone production is not determined solely by average power, but is also strongly influenced by voltage-current $(V - I)$ characteristics that reflect discharge dynamics, plasma filament formation, and energy distribution inside the reactor [4] [8].

Several studies have characterized the effect of voltage on ozone concentration using various types of mesh or spiral electrodes [6] [9] [10]. However, most of this literature has focused more on reporting ozone concentration and production capacity outputs without providing an in-depth analysis of the mechanistic relationship between electrical signal profiles and energy efficiency, represented by apparent specific energy input [4] [8]. SEI_{app}, defined as the ratio between injected apparent power and ozone production capacity, is a critical metric for evaluating the economic feasibility and performance of ozone generation systems [4] [11]. This knowledge gap causes operational optimization strategies to be carried out mainly empirically, without a comprehensive understanding of how filament current dynamics affect the efficiency of energy transfer into ozone formation.

In a double dielectric barrier discharge reactor configuration, the use of aluminum mesh electrodes offers unique potential for distributing the electric field more uniformly than solid or spiral electrodes [6] [9]. The physical characteristics of aluminum mesh can modify plasma dynamic resistance and discharge homogeneity, thereby directly affecting ozone formation and decomposition pathways [6] [10]. Despite this potential efficiency improveSment, literature specifically linking voltage-current characteristics to the SEI_{app} profile in DDBD systems with aluminum mesh electrodes remains very limited [4] [6]. Knowledge of how the electrical signature reflects the optimum point between maximum ozone production and minimum energy consumption is urgently needed for the development of optimal medical devices.

Therefore, this study aims to systematically analyze the effect of voltage-current characteristics on medical ozone production performance and energy efficiency in a DDBD plasma generator with aluminum mesh electrodes. Theoretically, this study seeks to establish a quantitative relationship between discharge dynamics and the resulting ozone capacity [8]. Practically, the results are expected to provide recommendations for operating parameters, especially in determining the optimum voltage and current ranges, in order to improve dose consistency and energy efficiency of ozone generators in accordance with the needs of modern clinical practice and strict medical standards [4] [6].

II. RESEARCH METHODS

➢ *Reactor Configuration and Design*

This study used a Double Dielectric Barrier Discharge reactor with a cylindrical geometry configuration. The reactor was designed with two dielectric barrier layers to ensure that pure oxygen gas did not come into direct contact with the electrodes, thereby minimizing contamination and making it highly suitable for medical applications [6]. The physical specifications of the reactor were as follows:

- Pyrex tube with a length of 18 cm, an outer diameter of 4 cm, and an inner diameter of 2.3 cm.
- Dielectric thickness of 0.275 cm with a discharge gap of 0.3 cm.
- Aluminum mesh electrodes with a length of 9 cm on both sides, with the outer electrode as high voltage and the inner electrode as grounding.

Mesh-type electrodes (Figure 1) were selected owing to their superior capability to distribute the electric field uniformly and enhance plasma homogeneity, outperforming conventional solid or spiral configurations [9]. This allows plasma filaments to form more uniformly along the electrode surface, thereby enhancing discharge homogeneity and energy transfer efficiency for ozone production while reducing local hot spots that may cause decomposition of newly formed ozone.

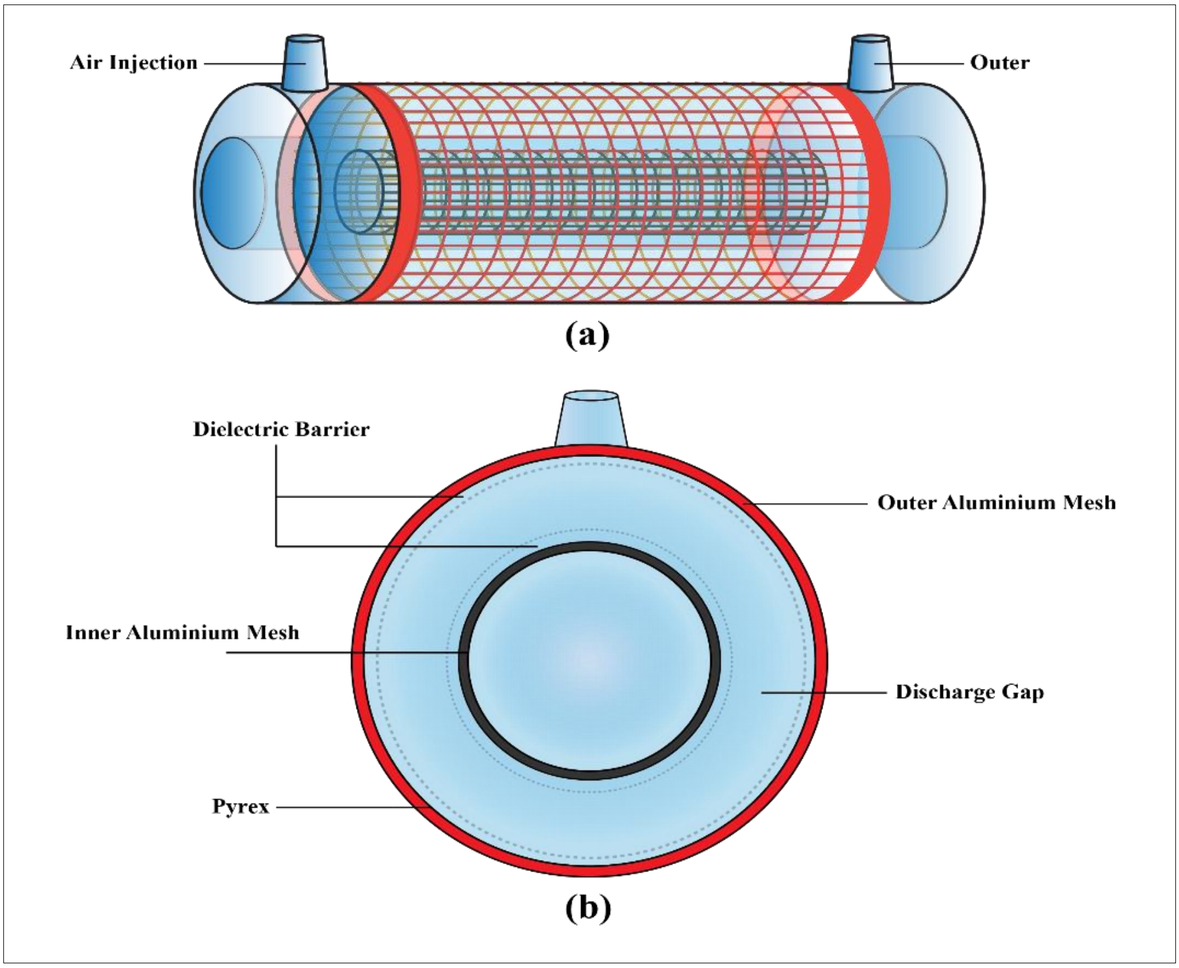

Fig 1 DDBD Reactor with Aluminum Mesh Electrodes: (a) Side View and (b) Front View

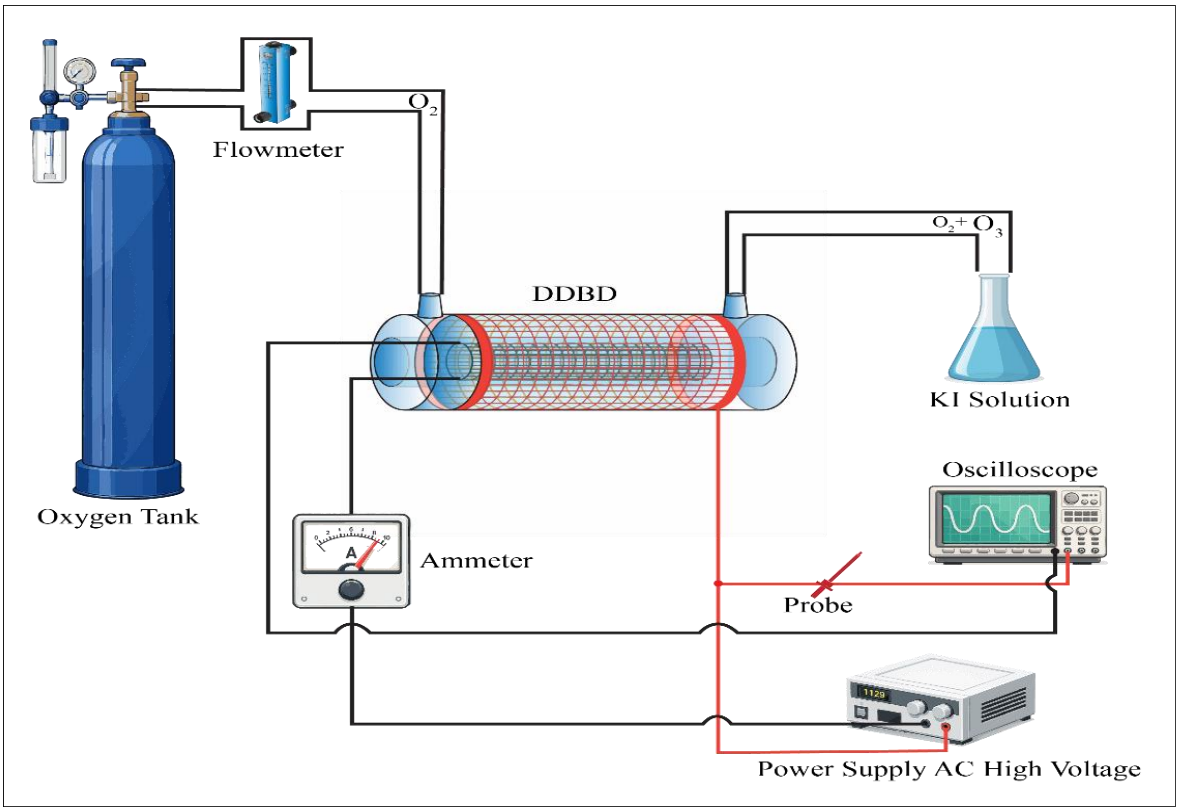

Fig 2 Schematic Diagram of the Experimental Setup

- *Power Supply and Measurement of V-I Characteristics*

The reactor was operated using a low-frequency 50 Hz sinusoidal alternating voltage source, which is one of the classical power supplies used in DDBD systems [12]. The voltage was varied in the range of 0.5 to 3.3 kV. The voltage-current characteristics were monitored in real time to analyze plasma dynamic behavior and microdischarge formation. Due to equipment limitations precluding the use of an integrating capacitor for standard Lissajous figure analysis, the apparent power was estimated by calculating the time-averaged integral of the voltage and current product ($P \approx \frac{1}{T}\int V(t)I(t)dt$). While this approach captures apparent power and may slightly overestimate the active power due to the inherent capacitive phase shift of the DDBD reactor, it provides a reliable comparative baseline for evaluating performance trends under a constant low-frequency (50 Hz) sinusoidal excitation. The experimental setup followed the arrangement shown in Figure 2.

- *Gas Flow System*

Medical-grade oxygen (>99.5% purity) served as the feed gas to preclude the formation of toxic nitrogen oxide byproducts [2] [6]. The gas flow rate was controlled using a flowmeter at 0.2, 0.4, 0.6, and 0.8 L/min. This flow-rate variation was intended to observe the effect of gas exposure time within the plasma zone on ozone concentration.

- *Measurement of Ozone Concentration and Production Capacity*

Ozone concentration was measured using the iodometric titration method, a standard and accurate technique for medical ozone determination [13]. Ozone was passed into a 0.2 M potassium iodide solution, as shown in Figure 2, for 2 minutes, triggering the reaction shown in Equation (1):

$$O_3 + 2KI + H_2O \rightarrow I_2 + O_2 + 2KOH \tag{1}$$

The solution was then titrated with 0.4 M sodium thiosulfate ($Na_2S_2O_3$) until the equivalence point was reached, indicated by a clear solution. Ozone concentration in g/L was calculated using Equation (2),

$$C = \frac{V_{titrant} \cdot N \cdot 24000}{Q \cdot t} \tag{2}$$

While ozone capacity or mass production rate was calculated using Equation (3),

$$\text{Capacity} = C \cdot Q \tag{3}$$

- *Calculation of Apparent Specific Energy Input*

Consequently, the energy efficiency was evaluated using an Apparent Specific Energy Input (SEI_{app}). Although the absolute values of SEI_{app} may encapsulate reactive energy components, the relative trends remain highly indicative of the system's thermal and collisional efficiencies across different flow rates. SIE_{app}, expressed in kWh/g or J/L, was calculated as the ratio of power to flow rate [14]:

$$SEI_{app}\ (kWh/L) = \frac{60 \times Power\ (kW)}{Flowrate\,(L/min)} \tag{4}$$

SEI_{app} analysis is very important for determining the optimum operating point at which maximum ozone production can be achieved with minimum power consumption [15].

- *Experimental Design and Data Analysis*

The experiment was conducted systematically with voltage variations of 0.5, 1.0, 1.5, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, and 3.3 kV, and oxygen flow rates of 0.2, 0.4, 0.6, and 0.8 L/min. Current measurements were repeated three times for each combination of voltage and oxygen flow rate used in the DDBD reactor to ensure data reproducibility. The collected data were analyzed to map the relationship between electrical characteristics and the profiles of ozone concentration, production capacity, and SEI_{app} [4] [6]. Strict safety protocols were applied, including the use of a ventilation system to prevent excessive ozone exposure in the laboratory area [1].

III. RESULTS AND DISCUSSION

- *Voltage-Current Characteristics and Apparent Power*

The experimental results showed that the current-voltage characteristics of the Double Dielectric Barrier Discharge reactor followed a nonlinear increasing trend that could be described by a quadratic relationship. This behavior indicates that once the breakdown voltage was reached, continuous microdischarges were formed within the gas gap, leading to a significant increase in electron density and discharge current [4].

Figure 3 shows that increasing the voltage from 0.5 to 3.3 kV increased the current at all oxygen flow rates of 0.2, 0.4, 0.6, and 0.8 L/min, following a quadratic trend in accordance with the equation I = 0.34653 – 0.52981V + 0.30919V^2 and $R^2 = 0.96094$. At low voltage, the current increased gradually, indicating that the system was still in the initial discharge regime. However, above approximately 2.0 kV, the current rose more sharply, suggesting that the applied voltage became the dominant factor governing charge transport in the reactor. At medium to high voltage, the 0.6 L/min condition tended to produce higher current values, while the 0.2 L/min condition generally produced lower values. The larger error bars observed at higher voltage indicate stronger response fluctuations and highlight the importance of optimizing the operating conditions for stable reactor performance. This condition emphasizes the importance of parameter optimization for system efficiency.

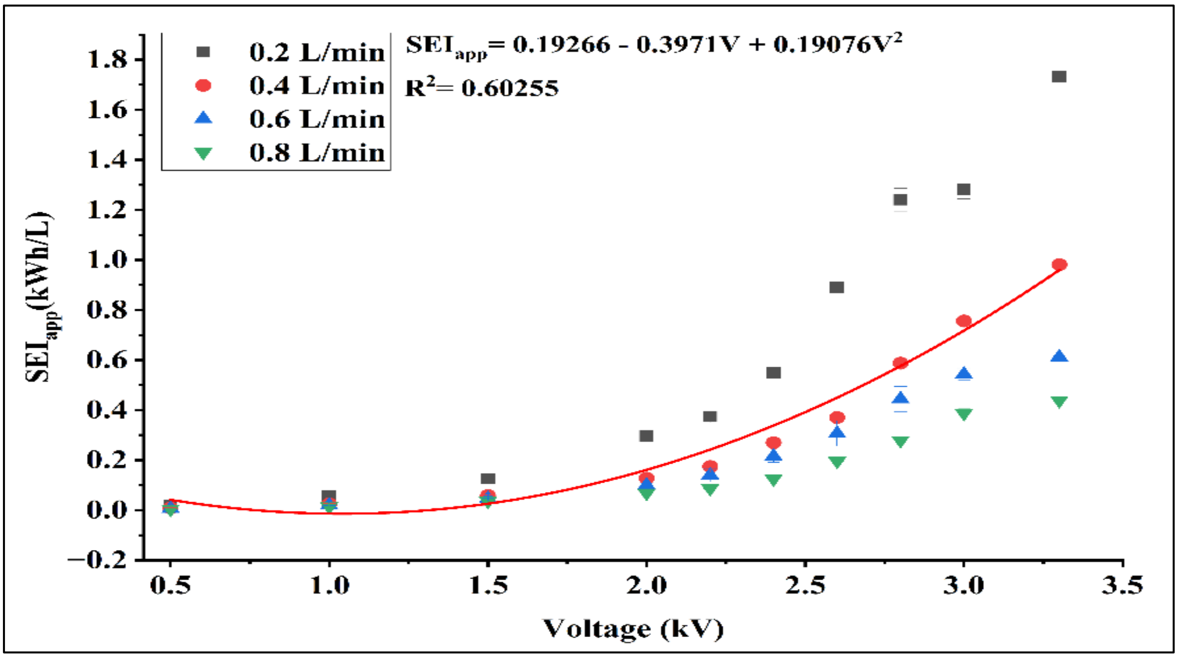

Fig 3 Voltage-Current Characteristics of the Double Dielectric Barrier Discharge Plasma Generator with Aluminum Mesh Electrodes at Various Oxygen Flow Rates

In line with the current characteristics, apparent power consumption also increased quadratically with operating voltage, as shown in Figure 4. Figure 4 shows that increasing voltage from 0.5 to 3.3 kV caused a sharp rise in power at all flow-rate variations of 0.2, 0.4, 0.6, and 0.8 L/min. The relationship is nonlinear and follows a quadratic pattern, in accordance with the equation P = 1.29036 – 2.64134V + 1.25477V² with $R^2 = 0.97296$, indicating excellent model fit. At low voltage, power remained small because the system was still in the initial transition phase and the input energy was not yet sufficient to generate maximum response. After exceedingly approximate 2.0 kV, power increased more rapidly, indicating the dominant influence of voltage on system output. At medium to high voltage, flow rates of 0.6 and 0.4 L/min tended to produce higher power, whereas the larger error bars indicate stronger response fluctuations and the importance of optimizing operating conditions. This occurs because more energy is transferred to electrons in the plasma, which accelerates the dissociation rate of oxygen molecules for ozone formation, but also increases heat dissipation in the reactor [4] [9].

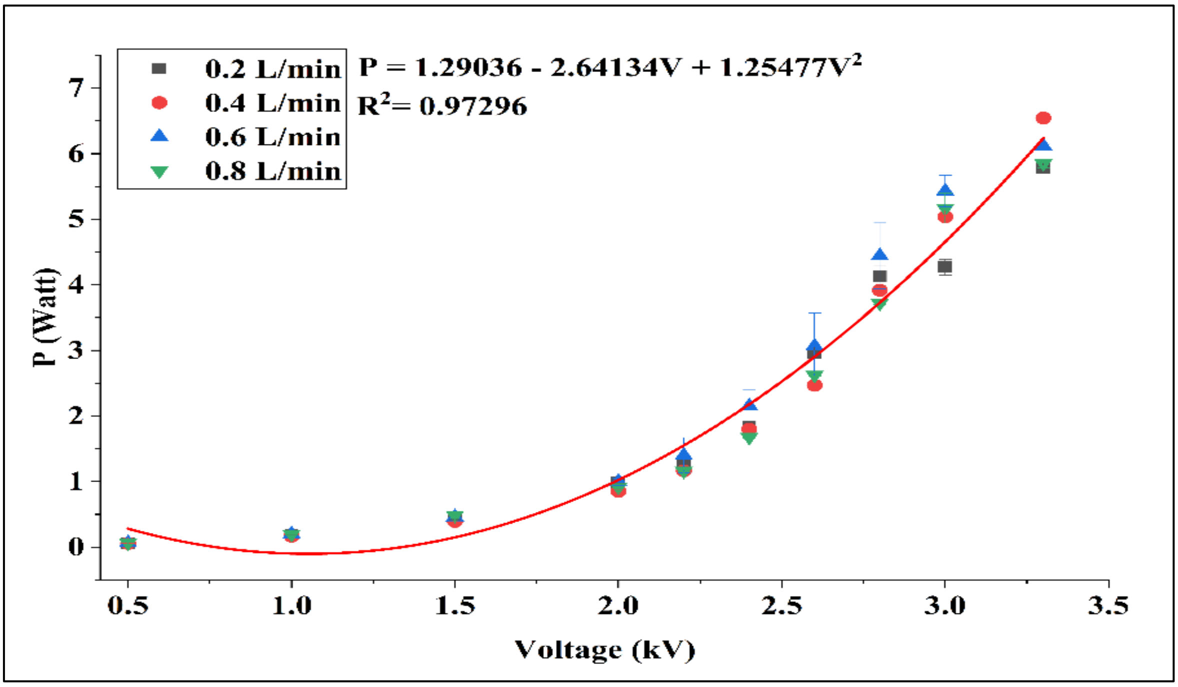

Fig 4 Voltage-Power Characteristics of the Double Dielectric Barrier Discharge Plasma Generator at Various Oxygen Flow Rates

- *Concentration and Capacity of Ozone Production*

The effect of gas flow rate on ozone concentration and ozone production capacity is shown in Figure 5. The two parameters show opposite trends.

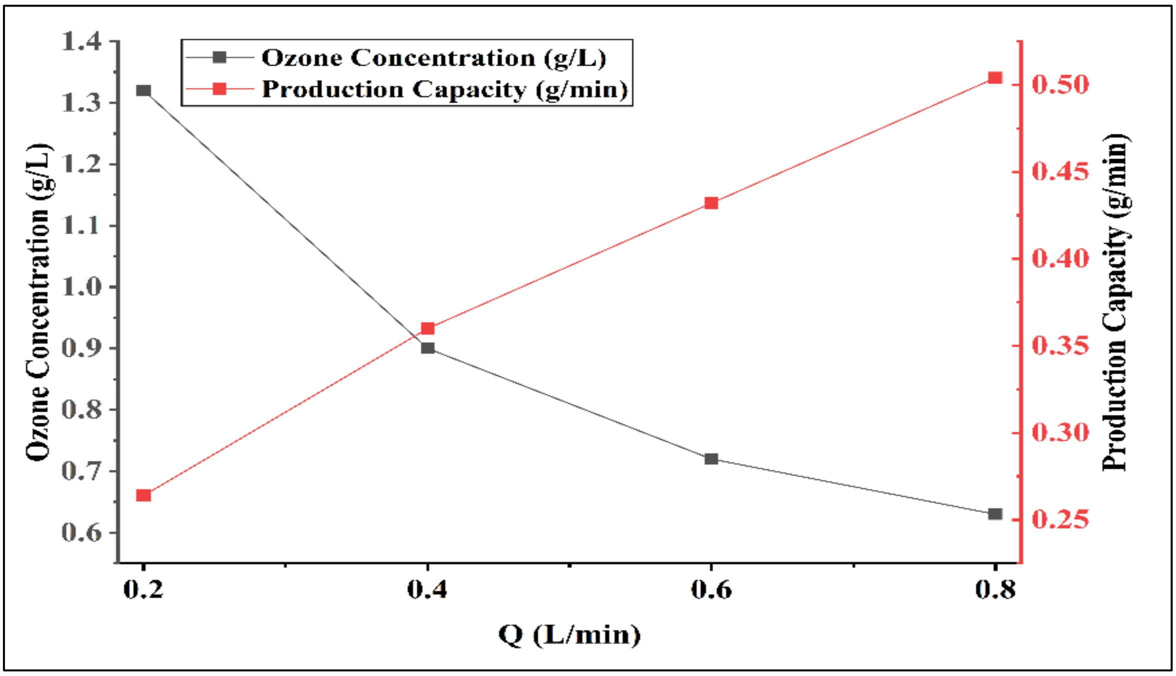

Fig 5 Effect of Oxygen Flow Rate on Ozone Concentration and Ozone Production Capacity

Ozone concentration decreased significantly from 1.32 g/L at a 0.2 L/min flow rate to 0.63 g/L at 0.8 L/min. This decrease is caused by the shorter exposure time of oxygen molecules within the plasma region, which lowers the probability of collisions between energetic electrons and gas molecules required for ozone formation [6] [16]. In contrast, ozone production capacity increased from approximately 0.27 g/min to approximately 0.51 g/min as the flow rate increased. Although the concentration decreased, the gas volume processed per unit time became much larger at high flow rate, so the total ozone mass produced per minute increased overall [16] [17].

Figure 5 shows an inverse relationship between feed gas flow rate and the two main parameters of the ozonation process, namely ozone concentration and production capacity. This trend confirms the existence of a trade-off between the quality of ozone produced and the amount of ozone generated per unit time. At low flow rate, gas residence time in the discharge zone is longer, so ozone formation per unit gas volume is higher, but the total ozone mass produced per minute remains limited. Conversely, at high flow rate, throughput increases, but ozone concentration decreases because of the shorter contact time. Interestingly, at a flow rate of 0.4 L/min, a relative balance between concentration and production capacity is observed, so this flow rate can be regarded as the most practically optimal and stable operating condition.

- *Apparent Specific Energy Input Analysis*

Apparent specific energy input is a crucial parameter for evaluating reactor energy efficiency. Figure 6 shows that SEI_{app} decreases and becomes more stable with increasing gas flow rate. At the low flow rate of 0.2 L/min, SEI_{app} variance is very high, with values reaching the highest range, indicating inefficiency caused by excessive gas heating inside the reactor [18]. Figure 6 shows that increasing the flow rate from 0.2 to 0.8 L/min tends to reduce SEI_{app}while also narrowing data dispersion. At 0.2 L/min, the SEI_{app} median is the highest, with the widest box and whiskers, indicating very large data variation and a system response that is still not homogeneous. The wide interquartile range shows that the data are spread far from the central value, while the extended upper whisker indicates that certain voltage conditions caused SEI_{app} to increase sharply. This suggests that at low flow rate, additional electrical energy is not always followed by a proportional increase in ozone production, making energy efficiency unstable.

When the flow rate increased to 0.4 and 0.6 L/min, the SEI_{app} median decreased and the data spread began to narrow, indicating more consistent system performance. At 0.8 L/min, the box plot is the narrowest with the lowest median, meaning that this condition is the most energy-efficient and stable. However, when evaluated for practical application as a whole, a flow rate of 0.4 L/min is more appropriate as the optimum operating condition because it provides a better balance among energy efficiency, ozone concentration, and ozone production capacity. Therefore, although 0.8 L/min is superior in terms of SEI_{app} stability, 0.4 L/min is more rational for practical application because it does not create an excessively large gap between the quality of the ozone produced and the production rate per unit time.

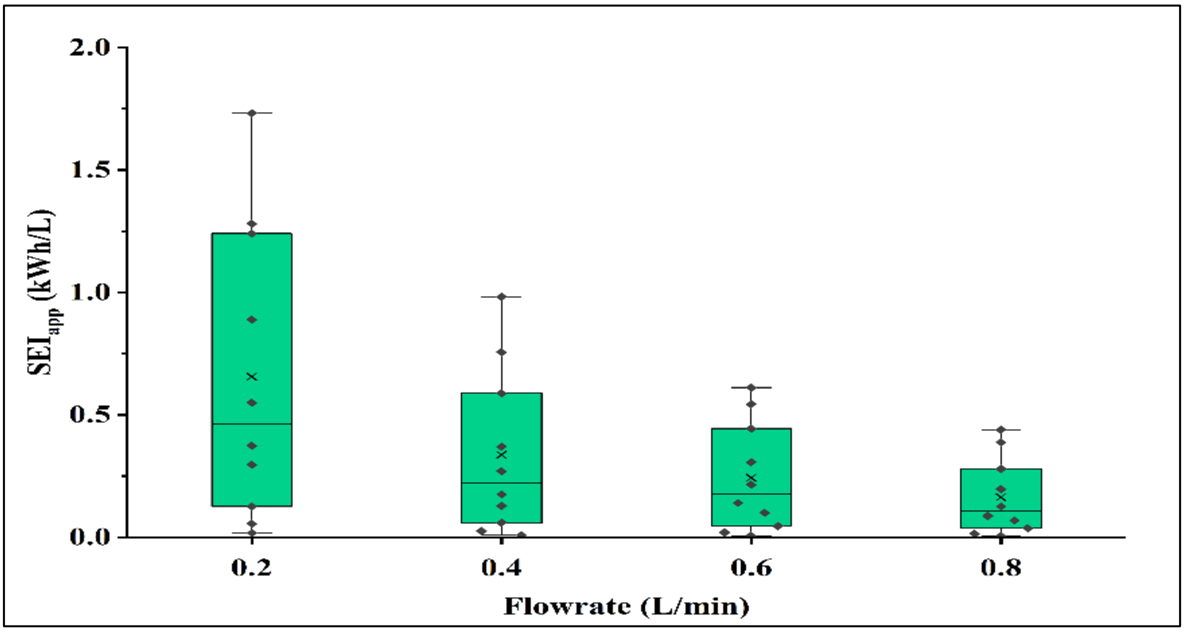

Fig 6 Distribution of Apparent Specific Energy Input at Various Oxygen Flow Rates

The relationship between SEI_{app} and operating voltage follows a quadratic pattern. Increasing voltage causes a very sharp rise in SEI_{app}, especially at low flow rate. This proves that at high voltage, most electrical energy is converted into thermal energy or excitation processes that do not directly contribute to ozone formation, making the energy cost per gram of ozone more expensive [19] [20].

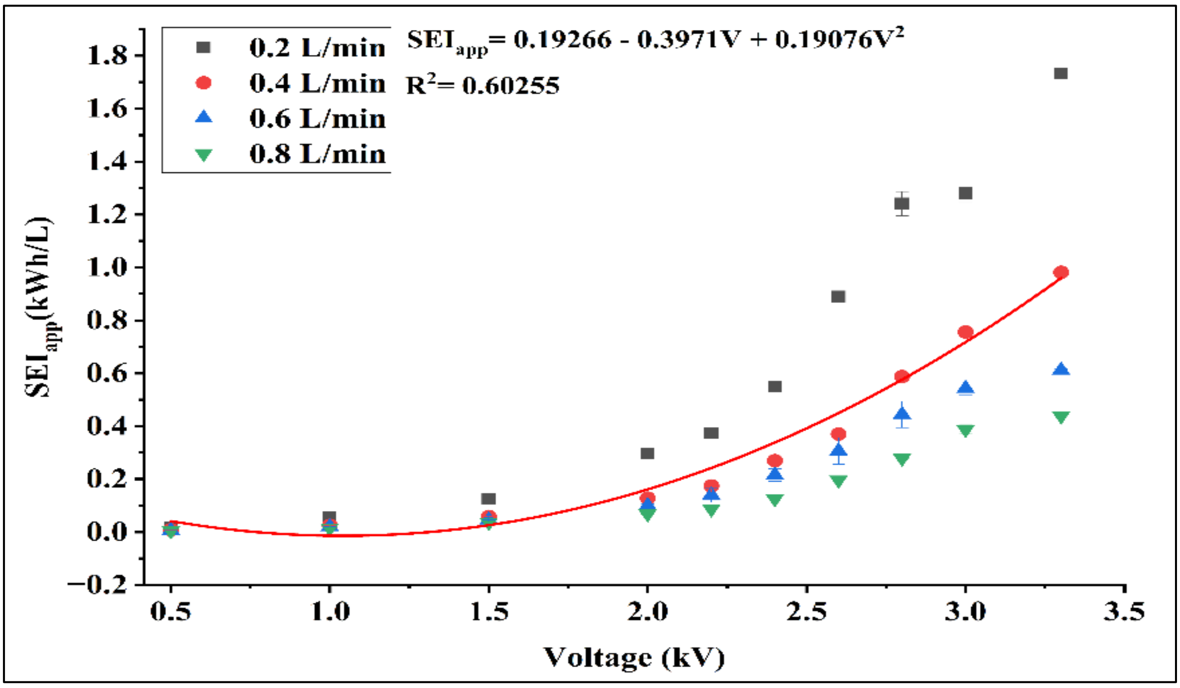

Fig 7 Effect of Operating Voltage on Apparent Specific Energy Input at Different Oxygen Flow Rates

Figure 7 shows that increasing the voltage from 0.5 to 3.3 kV tends to increase SEI_{app} at all flow-rate variations, especially after exceeding 2.0 kV. The relationship follows a quadratic tendency according to the equation SEI_{app} = 0.19266 – 0.3971V + 0.19076V², but the value of $R^2 =$ 0.60255 indicates that the model fit is only moderate, so the data variation among treatments remains fairly large. At a flow rate of 0.2 L/min, SEI_{app} becomes the highest and increases sharply at medium to high voltage, indicating a large specific energy requirement and lower process efficiency. In contrast, a flow rate of 0.8 L/min produces the lowest and more stable SEI_{app}. These findings confirm that increasing the flow rate can suppress specific energy consumption, whereas excessive voltage increase tends to enlarge the energy burden of the ozonator under operating conditions. The use of aluminum mesh electrodes in this DDBD configuration allows more homogeneous electric-field distribution, but optimization between voltage and flow rate is still required to achieve efficient medical ozone concentration [9] [21].

It is important to note the considerable variance in the SEI_{app}data, particularly at elevated voltages and lower flow rates ($R^2 = 0.60255$). This broad data dispersion is partially attributed to the direct V-I integration method utilized in this study. Without decoupling the displacement current via a Lissajous configuration, the calculated power incorporates non-active reactive components that fluctuate dynamically as microdischarge intensity escalates. Nonetheless, the overarching quadratic trend confirms that exceeding the optimal threshold severely compounds energy inefficiencies due to excessive thermal dissipation.

IV. CONCLUSION

Based on the results obtained using a Double Dielectric Barrier Discharge reactor with aluminum mesh electrodes, the voltage-current characteristics exhibited a quadratic trend, with both current and power increasing significantly as the operating voltage increased from 0.5 to 3.3 kV. This behavior indicates that higher voltage intensifies microdischarge activity and enhances oxygen dissociation inside the reactor. An inverse relationship was observed between ozone concentration and ozone production capacity with respect to oxygen flow rate. The highest ozone concentration was achieved at the lowest flow rate because of the longer residence time of oxygen molecules in the plasma zone, whereas the highest ozone production capacity was obtained at the highest flow rate because of the larger gas throughput. The SEI_{app} analysis showed that energy efficiency was strongly influenced by the interaction between voltage and flow rate. Higher flow rates reduced and stabilized SEI_{app}, while excessive voltage increased the energy burden of the system. Overall, the DDBD configuration with aluminum mesh electrodes proved effective for controlled medical ozone generation. For practical application, a flow rate of 0.4 L/min can be considered the most balanced operating condition because it provides a favorable compromise among ozone concentration, production capacity, and energy efficiency.

ACKNOWLEDGMENT

This research was partially supported through equipment assistance from the World Class Research University Scheme No: 222-747/UN7.D2/PP/IV/2025, from the Institute for Research and Community Service, Diponegoro University.

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