



Experimental Investigation of Ozone Generation in Multi-Cell Dielectric Barrier Discharge Reactors

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Abstract: Ozone is a sustainable oxidant with applications in water treatment, air purification, and food sterilisation. Dielectric barrier discharge (DBD) reactors are attractive for ozone generation because of their simplicity and scalability. Performance depends on both plasma processes and power supply characteristics. This research examined single-, two-, and three-cell dielectric tubes DBD reactor operated under varying voltages and frequencies to assess ozone yield and energy efficiency. FTIR spectroscopy confirmed ozone as the main product and enabled extended quantification beyond portable ozone detector saturation through calibration with detector readings ($R^2 = 0.9997$). Reactor scaling-up enhanced ozone generation, with the three-cell reactor achieving 11946 ppm and 17.25 g/h at 40 kV_{pp} and 100 Hz, for discharge voltage and frequency, respectively. However, ozone concentrations from the two- and three-cell reactors were nearly identical across the SEI (Specific Energy Input) range due to high-voltage power supply (HVPS) limitations rather than reactor design. Efficiency analysis revealed two perspectives, based on discharge power, the ozone production efficiency (OPE) peaked at 396 g/kWh in a two-cell configuration at low SEI but declined at higher SEI owing to non-productive energy losses. Conversely, the overall ozone production efficiency (OOPE), referenced to system input power, increased with SOEI (specific overall energy input), with the two-cell reactor outperforming (16.0–22.3 g/kWh). These findings highlight the combined influence of plasma on ozone generation, offering guidance for scaling DBD reactors in industrial applications.

Keywords: Ozone generation; nonthermal plasma; dielectric barrier discharge; FTIR spectroscopy; ozone production efficiency

1. Introduction

Ozone (O₃) is a colourless gas consisting of three oxygen atoms and characterised by a sharp, irritating odour [1]. Its physical and chemical properties are summarised in Table 1. Ozone is regarded as a strong oxidising agent [2], possessing an oxidation potential of 2.07 V [3] and exhibiting significantly lower stability than ambient oxygen, decomposing rapidly to oxygen in both air and water [4]. This rapid decomposition, which leaves no harmful residues, combined with high oxidising potential, makes ozone particularly advantageous for applications. In the food industry, it is used to inactivate microorganisms [5] and extend product shelf life [6], including vegetables, fruits [7], meat, and grain products [6]. As well as in drinking water treatment, ozone removes taste and

odour compounds (for example, geosmin and 2-methylisoborneol (MIB) by combining direct oxidation with ozone and indirect oxidation by hydroxyl (OH) radicals [8]. Ozone is also employed to enhance air quality through the removal of volatile organic compounds (VOCs), which pose direct risks to the eyes and the respiratory system [9].

Table 1. Physical and chemical properties of ozone.

Property	Value	Ref
Molecular weight (g/mol)	48	[1, 10]
Gaseous density (kg/m ³) @ 0 °C and 1 atm	2.1415	[11]
Solid density @ -195.75 °C (kg/m ³)	1728	[1]
Melting point (°C)	-192.5 ± 0.4	[1, 11, 12]
Boiling point (°C)	-111.9 ± 0.3	[1, 11, 12]
Half-life in air (min)	20 - 1524	[1]
Half-life in water (min)	10 -80	[1]
Dielectric constant at -183 °C	4.74	[1, 11]

A range of techniques has been developed for the generation of ozone, including vacuum ultraviolet (VUV) [13], electron-beam processes [14], water electrolysis [15], and electrical discharge plasmas such as Corona Discharge [16] and Dielectric Barrier Discharge (DBD) [17]. Among these, electrical discharge plasma remains the only practical approach capable of producing the quantities of ozone required for large-scale applications [18].

DBD is widely recognised as a non-thermal plasma (NTP) technique for ozone generation, an important oxidising agent with diverse industrial applications [19]. In this method, a high voltage AC (Alternating current) or pulsed DC (Direct current) is applied across a gas restricted between two electrodes separated by a dielectric barrier [20]. The resulting discharge produces reactive oxygen species (e.g., O), which subsequently interact with molecular oxygen to form ozone. DBD offers diverse advantages compared to other reactor types, including high efficiency, relatively low operating cost, and straightforward scalability, making it a desirable reactor design for ozone generation. Consequently, many researchers have investigated methods and operating strategies to produce high concentrations of ozone with low energy consumption to achieve greater efficiency. Xie Linjie et al. [21] studied the use of a coaxial DBD reactor with water as both the high-voltage and ground electrodes. The water electrodes effectively controlled the gas temperature, keeping the rotational temperature near ambient (305–308 K), which favoured ozone synthesis. As a result, the reactor achieved high ozone generation efficiency and stable long-term performance (6000 ppm ozone, which was maintained for 400 min). Sun Shukai et al. [22] developed a needle–plate DBD ozone generator with a magnetic field and showed that the field increased discharge power up to 23.9% and ozone concentration up to 35.4%. The findings suggested that magnetic fields enhanced ozone generation but did not improve the efficiency in this reactor design. Most studies emphasized the ozone production mechanisms at the laboratory scale, while fewer works focus on the effect of increased parallel DBD cell of a scale-up system.

The objective of this research is to investigate ozone generation in non-thermal plasma dielectric barrier discharge (NTP-DBD) reactors with different levels of DBD cell scaling, represented by single, two, and three-cell configurations. In this design, each “cell” corresponds to one dielectric tube discharge unit, and increasing the number of cells increases the effective discharge volume and surface area available for plasma reactions. To extend the high ozone concentration measure range, the study focused on quantifying ozone formation and byproducts using FTIR spectroscopy calibrated with an electrochemical-based ozone analyser. Moreover, evaluating the effects of applied voltage, frequency, and reactor scaling on ozone concentration and production rate, and assessing energy efficiency through both discharge-based ozone production efficiency (OPE) and system-based overall ozone production efficiency (OOPE). In addition, the work aimed to provide insights that support the optimisation and scale-up of multi-cell DBD reactors for practical environmental and industrial applications.

2. Materials and Methods

This research investigated how the number of reactor cells affects the electrical characteristics, ozone concentration, and ozone production efficiency in a DBD-NTP system. To evaluate the effect of system scaling, the reactor was operated in three configurations comprising one, two, and three cells, respectively, while the experimental arrangement for ozone generation is illustrated in Figure 1. The reactor was constructed from stainless steel and incorporates three borosilicate glass tubes as a dielectric barrier, each with an outer diameter of 63 mm, a glass tube thickness of 2 mm, and a length of 50 cm, which resulted in a discharge gap of 1.15 mm. The capacitance of the DBD reactors was measured by a Hioki LCR impedance analyser (model IM 3570). The measured values were 392.6 pF, 839.1 pF, and 1140.2 pF for the one, two, and three cells, respectively. The square-wave signal was generated using a digital storage oscilloscope (DSO) (KEYSIGHT, model DSOX1204G) and subsequently amplified using a high-voltage power supply (HVPS) (Trek 20/20C-HS) to generate plasma discharge. The discharge voltage was adjusted to 24, 30, and 40 kV_{pp} at frequencies of 50 Hz and 100 Hz. The electrical signals' instantaneous voltage and current were continuously monitored with the DSO to characterise the discharge behaviour. Additionally, the power consumption of the HVPS was also captured via a power meter. The feed gas consisted of air and oxygen, where the oxygen was supplied by an oxygen concentrator (purity is 93 %Vol.±3). Before entering the reactor, the gases were cooled and dehumidified to improve the stability of the discharge and enhance ozone generation efficiency [23, 24]. This step was particularly important, as water vapour can promote the formation of undesirable nitrogen oxides (NO_x) through the generation of OH radicals originating from water molecules [25].

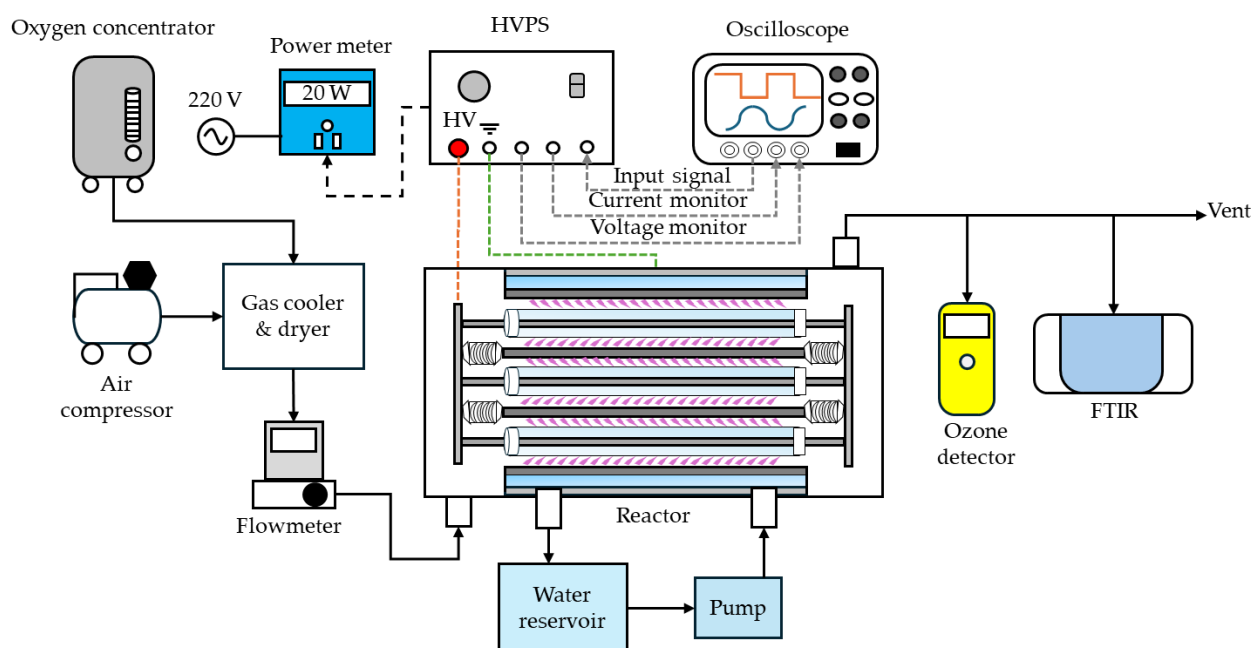


Figure 1. The schematic diagram of multi-cell DBD-NTP ozone generation.

The gas flow was controlled at 12 LPM with a flow meter (SMC, model: PF2A750 – F02 - 27) before entering the reactor. Moreover, the operating temperature of the reactor was regulated by a water-cooling system to prevent overheating of the reactor. This cooling system comprised a water reservoir and a pump, which circulated cooling water around the outer electrodes of the reactor.

UV absorption spectroscopy at 254 nm, based on the Beer–Lambert law, is a common approach [26] for ozone concentration measurement, though it can be affected by cross-interference, saturation at high concentrations, and sensitivity to temperature, pressure, and optical losses. Electrochemical sensing provides a simpler alternative by generating an electrical signal from ozone's reaction with an electrolyte [27], but this method is limited by electrolyte degradation and a restricted detection range. In this research, ozone concentration was initially monitored using an ozone analyser (SKZ, model: 1050-O₃). Due to the analyser's

measurement limit of 5000 ppm, a Fourier Transform Infrared Spectroscopy (FTIR) instrument (Bruker INVENIO R) was employed for higher concentrations. A calibration curve was established by plotting analyser readings against the integrated absorbance of ozone obtained from FTIR spectra, followed by linear regression to derive the calibration equation. This calibration enabled reliable quantification of ozone beyond the analyser's detection limit, allowing accurate measurement under varying operating conditions and reactor configurations. The ozone production efficiency (OPE, g/kWh), defined in Eq. (1), represents the efficiency of ozone generation based on the discharge power. The overall ozone production efficiency (OOPE, g/kWh), given in Eq. (2), accounts for the proportion of ozone generated relative to the total input energy, including the contribution from the HVPS.

$$OPE = \frac{OPR}{P_D} \times 1000 \quad (1)$$

$$OOPE = \frac{OPR}{P_m} \times 1000 \quad (2)$$

Where OPR is the ozone production rate (g/h), which describes how much ozone is produced per unit time and can be calculated using Eq. (3). P_D is the discharge power (W) calculated from Eq. (4) [28]. P_m (W) represents the total power consumed by the HVPS as measured directly with a power meter.

$$OPR = C_{O_3} \times Q \times 60 \quad (3)$$

Where C_{O_3} is ozone concentration (g/L), and Q is the gas flow rate (LPM)

$$P_D = f \times \int_0^T I(t) \times V(t) dt \quad (4)$$

Which $I(t)$ and $V(t)$ are the current and voltage signals, respectively. f is the frequency (Hz) and T is the period of discharge.

The Lissajous diagram of the DBD ozone generator requires both the reactor voltage and the corresponding charge. In the conventional approach, a measurement capacitor is connected in series with the reactor, and the charge (Q) is determined from the voltage across this capacitor multiplied by its capacitance. However, the addition of a measurement capacitor can increase the overall capacitance of the reactor, thereby altering its electrical characteristics. To avoid this effect, a virtual measurement capacitor was introduced, and the charge was reconstructed by integrating the measured discharge current. As the oscilloscope provides discrete data points, numerical integration was applied, and the accumulated charge is expressed as eq. (5) [29].

$$Q(t) = \sum_{i=1}^N I(t_i) \Delta t \quad (5)$$

Where $I(t_i)$ is the discharge current at time (t_i), Δt is the data sampling interval, and N is the number of samples.

The energy consumption and the formation of reactive species in the discharge process were directly related to the specific energy input (SEI, J/L), which was calculated as shown in Eq. 6 [30]. Furthermore, the total energy supplied by the HVPS, expressed as the specific overall energy input (SOEI, J/L), is defined in Eq. (7).

$$SEI = \frac{P_D}{Q} \times 60 \quad (6)$$

$$SOEI = \frac{P_m}{Q} \times 60 \quad (7)$$

3. Results and Discussion

3.1 Electrical behaviours

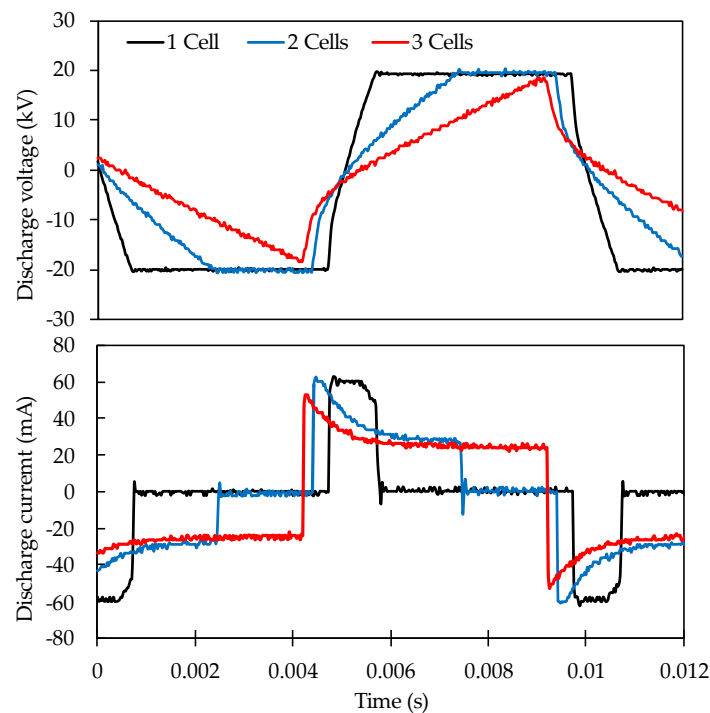


Figure 2. Discharge voltage and discharge current waveform.

Figure 2 demonstrates the discharge voltage and discharge current waveform of one, two, and three DBD cells when applying a discharge voltage at 40kVpp 100 Hz. The discharge voltage waveform indicated a difference when increasing the number of DBD cells. For the single-cell configuration, the discharge voltage shows a slightly skewed square wave as the result of the limited slew rate of the HVPS (800 V/ μ s) and the substantial capacitance of the DBD reactor. On the other hand, the 2 and 3-cell configuration indicated a significantly lower gradient of voltage waveform during both positive and negative phases. This phenomenon is due mainly to the capacitive load characteristic of the DBD reactor, whose capacitance of the reactor increased with the number of DBD (borosilicate glass) and affected the charge and discharge characteristics. In the case of the configuration with three DBD cells, the maximum voltage attained was lower than that observed with one or two DBD cells. This discrepancy is attributed to insufficient time for complete reactor charging, which consequently led to a reduction in discharge power. A detailed analysis of this effect will be presented in a subsequent section. The current waveform was steep and narrow in the single-cell case, whereas the two- and three-cell configurations exhibit broader waveforms with peak amplitudes half as high. The peak current reaches approximately 60 mA, which was the peak current limited (clipped) by the HVPS. Moreover, the current waveforms show a more leading phase characteristic as the number of cells increases. The ability of the HVPS to deliver high voltage is constrained by its slew rate, which for the Trek 20/20C-HS is limited to 800 V/ μ s, which means it requires at least 50 μ s to drive the output stage to 40kV. The high capacitance of our proposed DBD reactor imposed a significant capacitive load, preventing the HVPS from supplying current rapidly enough to effectively charge it in a finite period.

The dielectric properties of the DBD reactors were further evaluated using Lissajous diagrams, which provided insight into the capacitive behaviour of the multi-cell DBD. As shown in Figure 3, the slope of the charge–voltage (Q–V) curve, corresponding to dQ/dV [31], indicated the dielectric capacitance of the reactor. Linear fitting of each curve revealed capacitance values of 471.1 pF, 998.39 pF, and 1219.2 pF for the one, two, and three cell configurations, respectively. These values increased proportionally with the number of cells and indicated good agreement with the measurement values obtained from the LCR meter. In addition, the

enclosed area of each Lissajous parallelogram represents the energy dissipated per cycle of discharge. It is evident that the area becomes larger with the addition of more cells, reflecting higher discharge power and increased energy deposition into the plasma

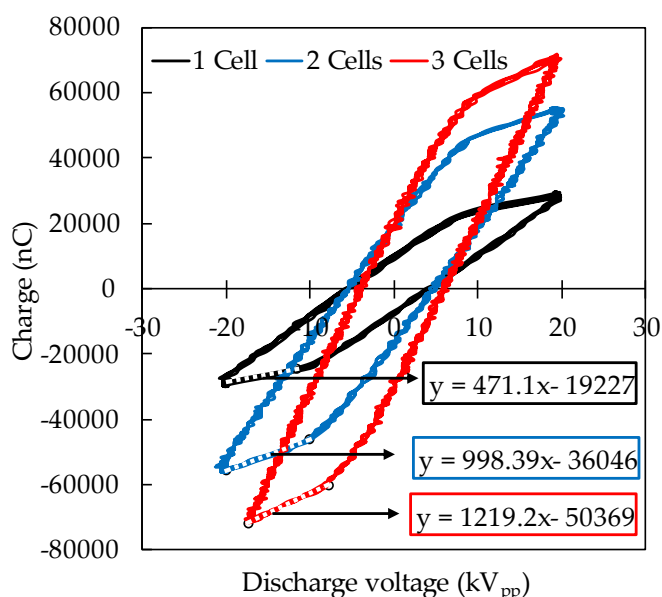


Figure 3. Lissajous diagram of multi-cell DBD at 40kV_{pp} and 100 Hz.

3.2 Ozone formation and quantification

Ozone is produced from oxygen dissociation mechanisms (R1) and (R2), followed by three-body recombination to ozone (R3) [32].



Which M is the third body that removes excess energy, e.g., O, O₂, or N₂.

Figure 4 presents the FTIR spectra obtained during ozone generation with a three-cell DBD configuration operated at different applied voltages (24, 30, and 40 kV_{pp}) at a fixed frequency of 100 Hz and utilising air+O₂ at 12 LPM. The spectra revealed the main gaseous products formed in the discharge corresponding to the ozone band. Besides, minimising other absorption is byproduct NO_x species from nitrogen in air, such as nitrous oxide (N₂O), dinitrogen pentoxide (N₂O₅), and carbon dioxide (CO₂). The absorption bands for these gases are summarised in Table 2. At 24 kV_{pp}, the ozone absorbance was relatively weak, indicating limited generation efficiency at lower discharge power. Increasing the voltage to 30 kV_{pp} resulted in a significant rise in the absorbance, and at 40 kV_{pp}, the ozone peak became dominant. This confirmed the strong dependence of ozone formation on the discharge intensity. This trend was consistent with higher applied voltages enhancing the electron energy distribution, thereby promoting more effective oxygen dissociation and subsequent ozone formation.

Table 2. Reference infrared absorption bands of ozone and related species.

Species	Band/cm ⁻¹	Ref
O ₃	1050, 2100	[33]
N ₂ O	1300, 2211, 2237	[34]
N ₂ O ₅	1247, 1720	
CO ₂	2360, 2340	

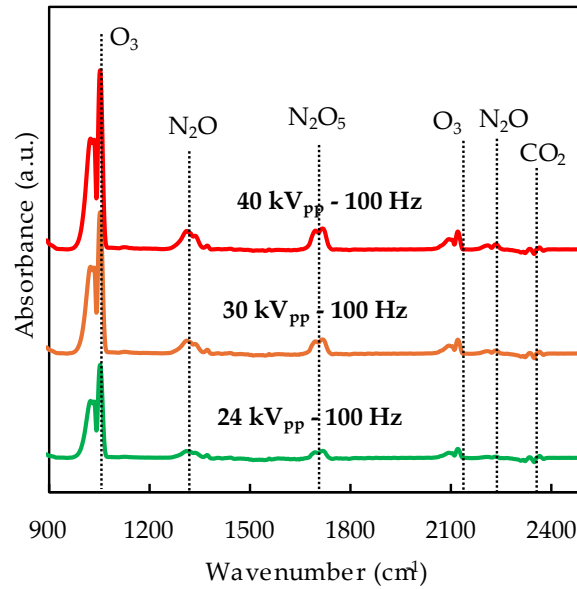


Figure 4. FTIR spectra of ozone generation at 3 cells configuration.

The NO_x species originated from N₂ in the air feed, with pathways such as N₂O formed via (R4) – (R5) and N₂O₅ formed via (R6) – (R9) [34].

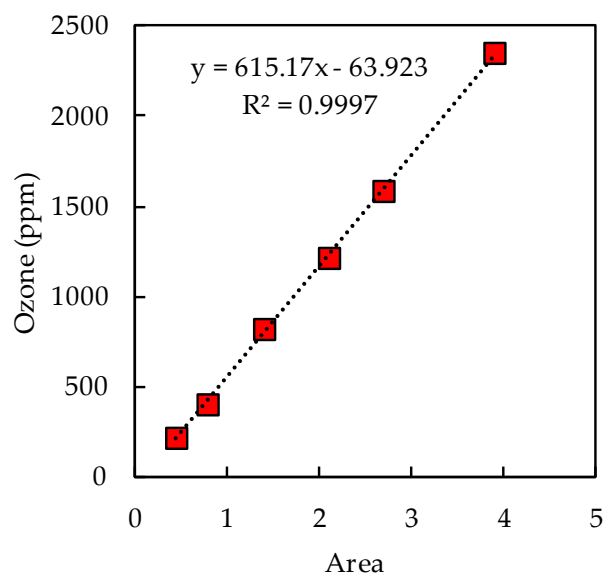


Figure 5. Calibration curve for ozone concentration.

The ozone analyser (SKZ1050) alone was unable to measure concentrations exceeding 5000 ppm-vol. FTIR spectroscopy was calibrated with the ozone analyser to extend quantification beyond this range. The calibration curve was established by correlating the ozone analyser readings with the integrated area under the ozone absorption curve obtained from FTIR spectra. As illustrated in Figure 5, this calibration produced a strong linear relationship, expressed as $y = 615.17x - 63.923$ with a coefficient of determination (R^2) of 0.9997. During the experiments, the discharge power of the reactor was incrementally adjusted, and data from both the ozone analyser and FTIR were collected simultaneously. The data's linearity confirms this approach's reliability, demonstrating that FTIR can be utilised to accurately quantify ozone concentrations once the ozone analyser's detection range exceeds the measurement range of SKZ1050.

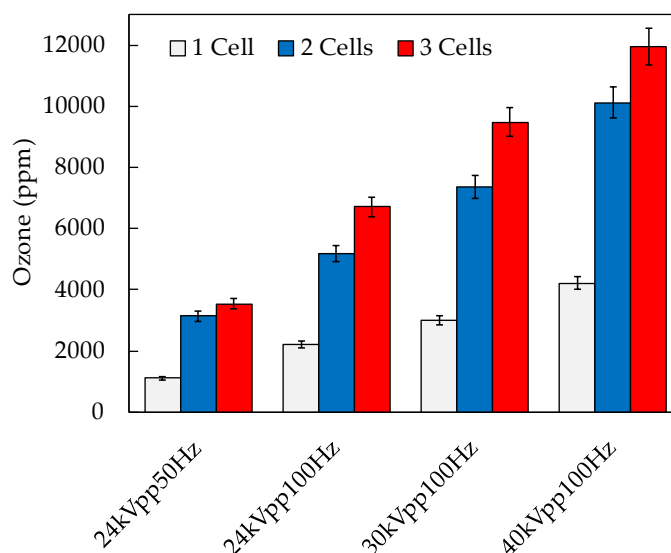


Figure 6. Compares the ozone concentrations produced for one, two, and three cells.

Figure 6 demonstrates the comparison of the ozone concentrations produced under four different operating conditions (24–40 kV_{pp} at 50–100 Hz) for one, two, and three cell configurations. The results demonstrated that ozone concentrations increased with the number of cells. Increasing the number of cells from one to three significantly enhanced ozone generation across all condition voltages and frequencies. This can be explained by the fact that the larger effective discharge volume and surface area are provided by increasing the dielectric tubes, which promoted a greater number of micro discharges per cycle. As a result, a larger fraction of the input energy was converted into plasma reactions, leading to higher ozone concentrations. In addition, at 24 kV_{pp} and 50 Hz, the ozone concentrations were approximately 1100 ppm, 3100 ppm, and 3500 ppm for one, two, and three cell configurations, respectively. When the frequency was increased to 100 Hz while maintaining the same voltage (24 kV_{pp}), ozone production increased, reaching approximately 2200 ppm, 5150 ppm, and 6700 ppm for one, two, and three cells, respectively. A similar increasing trend was observed at higher discharge voltages. At both 30 kV_{pp} (50 Hz) and 40 kV_{pp} (100 Hz), ozone production rose further across all cell configurations, demonstrating that both applied voltage and operating frequency have a significant effect on ozone generation [7]. The highest ozone concentration was obtained at 40 kV_{pp}, 100 Hz in the three-cell configuration, highlighting the combined benefit of higher voltage, higher frequency, and reactor scaling.

Figure 7(a). reveals the variation in the concentration of ozone with SEI. The ozone concentration rose linearly with SEI in all reactor configurations. The three-cell setup produced the highest concentration, reaching 11946 ppm-vol at 627 J/L, while the single cell configuration only generated ozone below 6000 ppm compared to the same conditions. However, the concentrations obtained with the two- and three-cell reactors were nearly identical within the same SEI range. This similarity was attributed to the HVPS's inability to provide enough power to fully charge the three-cell setup, caused by the high reactor's capacitance. Figure 7(b). showed a similar trend, with the ozone production rate increasing gradually with SEI. The three-cell

setup achieved a maximum production rate of 17.25 g/h. This demonstrated how increasing the number of discharge cells increased not only the effective discharge volume but also enhanced the ozone generation. Contrasting with the linear increase in ozone concentration, the ozone production efficiency decreased with increasing SEI, as shown in Figure 7(c). At low SEI below 100 J/L, the three-cell reactor achieved approximately 305 g/kWh. At higher SEI (340 - 630 J/L), OPE dropped significantly and remained around 140 g/kWh for all configurations. This was caused by an increasing amount of input energy to the reactor, dissipated as heat and other non-productive processes at higher discharge powers. Although the multi-cell systems maintain improving on the single-cell configuration, the relative advantage is reduced at high SEI. A different trend showed when the overall ozone production efficiency (g/kWh) was calculated based on the system input power shown in Figure 7(d). During the SOEI range, the two-cell reactor consistently produced the highest OOPE (16.0→22.3 g/kWh), followed by the three-cell reactor (14.6→22.6 g/kWh) and the single-cell reactor (6.6→13.9 g/kWh). This behaviour indicated the correlation between wall-plug efficiency and HVPS operating conditions. At low input power, the supply exhibited lower conversion efficiency and power factor. As SOEI increased, relative electrical losses decreased, and apparent efficiency improved. The three-cell's slightly lower OOPE when compared to two cells was due to the significantly greater capacitive load, which utilised the HVPS over its current/slew-rate limits (as indicated by broadened current pulses and softened voltage slopes), introducing additional supply losses and preventing full utilisation of the extra discharge capacity. OOPE provides a realistic measure of the energy cost of ozone generation from the end-user's perspective, while OPE (discharge-based) only reflects the intrinsic plasma efficiency of the reactor.

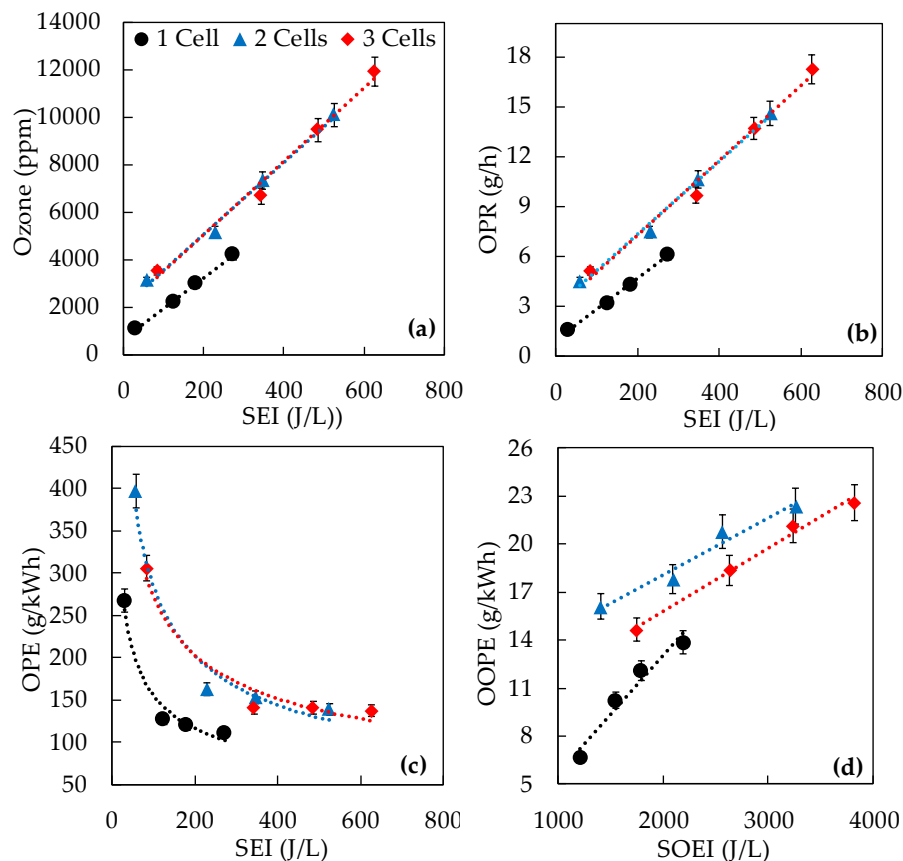


Figure 7. The Ozone production as a function of specific energy input, expressed in terms of (a) concentration (ppm), (b) ozone production rate (g/h), (c) ozone production efficiency based on discharge power (g/kwh), and (d) overall ozone production efficiency based on HVPS power (g/kwh).

The limits of the HVPS under various capacitive loads are presented in Figure 8, where each curve corresponds to a different load's capacitance. The shaded area indicated the discharge voltage and frequency

window utilised in this research, thereby additionally ensuring that all experimental operating points were located within stable supply conditions. The one-cell (471 pF), two-cell (998 pF), and three-cell (1219 pF) reactors' capacitances were all found in this region, demonstrating that the HVPS could drive each configuration at the given frequencies. Increasing the number of cells expanded the discharge volume and raised the energy input. However, this did not transfer into an improvement in ozone concentration, OPR, or OPE. In contrast, when efficiency is assessed from the perspective of the actual power drawn from the wall socket, the OOPE improved consistently with each additional cell.

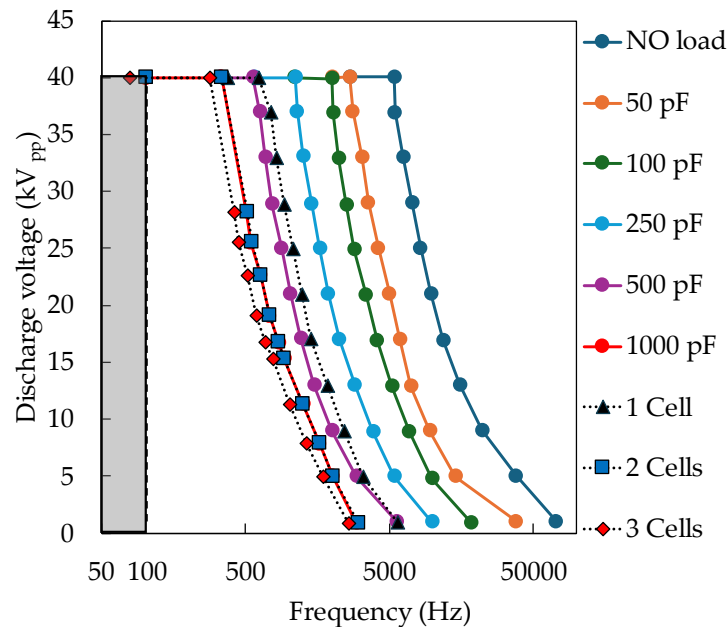


Figure 8. Operational frequency range of HVPS under different capacitive loads and DBD Cell Configurations (Adapted from Advanced Energy).

4. Conclusions

This research has demonstrated that scaling DBD reactors from one to three cells significantly enhances ozone generation by increasing the effective discharge volume and effective surface area. However, the merits of increasing reactor capacity were limited by the output capacity of the HVPS. The observed reduction of discharge voltage slope was restricted by the slew rate of the HVPS, while the broadened current pulses resulted from the current clipping function of the HVPS. Energy efficiency analysis revealed two complementary perspectives. OPE, referenced to discharge power, was highest at low SEI. On the other hand, OOPE, which accounts for HVPS performance, provided a more realistic measure of system efficiency and real ozone production cost. In this respect, the two-cell reactor achieved the most favourable balance between ozone yield and power utilisation, while the three-cell configuration was restricted by the limitations of the HVPS. In summary, ozone generation efficiency in DBD reactors was governed by both plasma processes and HVPS performance. While reactor scaling enhances ozone yield, system-level efficiency was maximised when the power supply could operate efficiently under the corresponding electrical load. These findings provided valuable guidance for developing energy-efficient ozone generators for practical applications in water treatment, air purification, and food sterilisation. Future work should focus on applying multi-cell DBD reactors in practical fields such as water and wastewater treatment, air purification, and food sterilisation, where high ozone yields are required. The results also provide valuable guidance for engineers who wish to scale up ozone generators for industrial applications, enabling more sustainable and energy-efficient processes.

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