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The impact of dielectrics on the electrical capacity, concentration, efficiency ozone generation for the plasma reactor with mesh electrodes

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Abstract
This paper presents experimental results concerning the effect of dielectric type on ozone concentration and the efficiency of its generation in plasma reactor with two mesh electrodes. Three types of dielectric solid were used in the study; glass, micanite and Kapton insulating foil. The experiments were conducted for voltage ranges from 2.3 to 13 kV. A plasma reactor equipped with two 0.3 × 0.3 mm² mesh electrodes made of acid resistant AISI 304 mesh was used in the experiments. The influence of the dielectric type on the concentration and efficiency of ozone generation was described. The resulting maximum concentration of the ozone was about 2.70–9.30 g O₃ m⁻³, depending on the dielectrics used. The difference between the maximum and the minimum ozone concentration depends on the dielectric used, this accounts for 70% at the variance. The reactor capacity has also been described in the paper; total Cᵣ and dielectric capacitance C_d depending on the dielectric used and its thickness.

Keywords: ozone generation efficiency, dielectric, mesh electrode, ozone generator, electrical capacity

(Some figures may appear in colour only in the online journal)

1. Introduction

Ozone systems also known as plasma reactors have been known for more than 100 years [1]. Many researchers around the world are conducting experimental research on improving the work parameters of ozone generators [2–4]. Classic systems have a simple structure consisting of two electrodes separated by a solid dielectric. The most commonly used dielectric is glass [5], other dielectrics e.g. acrylic glass, ceramic dielectrics are also used in DBD plasma reactor [6]. Dielectric prevents arc arcing and increasing the local temperature what is the effect of decreased concentration and ozone generation efficiency. There are many factors, including power supply voltage, supply voltage [7], type of gas used [8], electrode geometry [9–11], discharge gap and type of dielectric [10, 12, 13]. The use of dielectric with high dielectric constant allows to change the parameters of the reactor’s work. This paper analyzes the effect of the different types of solid dielectric on the concentration and efficiency of ozone generation. Three types of dielectrics used in experimental research are glass, micanite, and insulation foil Kapton.
2. Materials and methods

Experiments were carried out with the plasma display shown in figure 1 [14]. Measurement of the plasma reactor operating parameters and power supply of the layout system shown in figure 2, consisting of: an autotransformer, a high voltage transformer 230/10.000 V, a gas flow-meter model Bronkhorst F-201CV-1K0-AAD-V-44, ozone analyzer BMT 961TC, for the measurement of the voltage and the current used oscilloscope Tektronix TDS 2024B, equipped with a high voltage probes Tektronix P6015A, and a current probe Tektronix P2220. The built-in reactor consists of two mesh electrodes separated by a dielectric constant. Experimental researches were carried out with electrodes of mesh size 0.3 \( \times \) 0.3 mm\(^2\). Mesh electrodes are made of stainless steel grade AISI 304. Stainless steel does not oxidize, which allows maintaining stable and unchanging operating conditions of the reactor. The use of a 0.3 \( \times \) 0.3 mm\(^2\) small wire electrode shown in figure 1(b) allows for even tensioning of the electrodes on the adjusting rings. Built reactor can operate in one of two configurations: the first when the gas flows perpendicularly through the GND mesh electrode, the discharge gap, porous dielectric and high voltage mesh electrode. In the second configuration of the system it is possible to use one gas permeable electrode and the use of gas-impermeable dielectrics. Change of flow of gas available is dependent on the desired configuration of the opening or closing of output 1 and output 2 gas. The presented experimental results in this paper were obtained for the reactor configuration shown in figure 1(a), with one gas permeable electrode mesh and impervious dielectric. The dimensions of the reactor, 90 mm in diameter, 150 mm in length the others conditions of the experimental studies are shown in table 1.

Three types of dielectric constants have been used in experimental studies. The most commonly used dielectric is glass. In the experimental research were used, a glass dielectric with a thickness of 1.1 mm, as well as a micanite dielectric thickness of 1.0 mm and two layers of Kapton insulation of 0.05 mm each. Dielectric were placed directly on one of the reactor’s electrodes as shown in figure 3. Figure 4 shows the solid dielectrics used in experimental research. Oxygen and nitrogen at 0.5 l min\(^{-1}\) are used as process gas. Nitrogen was used for visualization of the discharges (making photos). During the experiments were application of 50 Hz frequency power supply. Power supply with frequency 50 Hz is simple, which significantly simplifies the construction of the system is less emergency and cheaper.

The dielectric glass is the most popular dielectric used in ozone generators, is an excellent comparison of results for other dielectrics. Another dielectric used in the experimental researches were micanite, is commonly used as insulating material in heating. The micanite dielectric thickness was similar as the glass dielectric, which allows to easily compare the generation of ozone for both dielectrics. The last dielectric was Kapton insulation foil, the dielectric constant was similar to the micanite dielectric. The thickness of the insulating foil Kapton was much smaller than the dielectric micanite which allows to check the effect of the dielectric thickness on the generation of ozone.
3. Results and discussion

3.1. Glass dielectric

The first session of the experimental research was carried out for 0.3 × 0.3 mm² mesh electrodes, 1.1 mm thick dielectric glass and 0.5 mm discharge gap for 0.51 min⁻¹ oxygen flow. The glass dielectric used in this experimental research was sodium glass. During the study, ozone concentration was recorded for individual voltage ranges from 3020 to 13 200 V. The maximum concentration of ozone obtained for the glass dielectric was 5.15 g O₃ m⁻³.

The discharge power was determined by the Lissajous figures recorded for each voltage range. Selected oscillograms, Lissajous figure, and waveforms of voltage and current are shown in figure 5.

3.2. Micanite dielectric

Another series of experiments were performed for 1.0 mm micanite dielectric, 0.3 × 0.3 mm² mesh electrodes and 0.5 mm discharge gap length. The dielectric was the same as the glass dielectric shown in figure 3, placed directly on the mesh electrode. The experiments were conducted for the voltage range of 4510 to 13 900 V. Determination the power was possible thanks to the registered Lissajous figures for individual voltage ranges. Selected oscillograms of the Lissajous figure and voltage and current waveforms are shown in figure 6.

The maximum power for micanite dielectric was 1.3 W with an ozone concentration of 2.70 g O₃ m⁻³.

3.3. Dielectric Kapton foil

The last research was carried out for a dielectric made of Kapton insulation foil. Two layers of 0.05 mm thick Kapton foil were used for the experiment. Each dielectric thickness was 0.1 mm. Voltage range was from 2360 to 8270 V. Due to the possibility of damage to the dielectric Kapton foil, a lower voltage range was used compared to the other dielectrics. Lissajous figures were used to determine the power, the selected figure is shown in figure 7.

The ozone concentration obtained for the Kapton foil dielectric was 9.30 g O₃ m⁻³ and it was the largest ozone concentration during the experimental studies for all dielectrics.

4. Analysis of results

The results of the experiments were used to analyze the effect of the dielectric type on the concentration and efficiency of ozone generation. Selected parameters and experimental results are shown in table 2. One of the parameters determining the effect of dielectric type on ozone generation was the measurement and comparison of the ozone concentration for individual dielectrics. Figure 9 shows the comparison of ozone concentration for glass, micanite and Kapton foil dielectrics.

From the analysis of figure 8, it can be concluded that the highest concentration of ozone was obtained for Kapton foil dielectric 9.30 g O₃ m⁻³. A slightly lower ozone concentration was obtained for a glass dielectric of 5.15 g O₃ m⁻³. Ozone concentration recorded for Kapton foil dielectric was 55% greater than for glass dielectric.

Another parameter describing the effect of dielectric on ozone generation was the efficiency of the ozone generation that was presented for individual dielectrics in figure 9.

By analyzing the graphs as depicted in figure 9, the highest efficiency of ozone generation was achieved with a dielectric foil Kapton average of 127 g O₃ kWh⁻¹ and for a dielectric glass of 81 g O₃ kWh⁻¹. The efficiency of ozone generation for glass dielectrics was 60% lower than that of Kapton foil dielectric.

From the presented research and the analysis of the obtained results, the dielectric type has a clear influence on the concentration and efficiency of ozone generation. The change in the concentration and efficiency of ozone generation results from the fact that the dielectrics used have different physical properties, among others dielectric constant ε (F m⁻¹) which was respectively for each dielectric Kapton 3.5–4.0 insulation foil, soda–lime glass 6.0–8.0, micanite 3.0–6.0 [15]. With the change in the dielectric constant, the reactor total capacity has changed. The total capacity of the reactor consists of the capacity of two flat capacitors connected in series (C_a air capacitor and C_d capacitor with the dielectric), shown in figure 10.

The first capacitor was a flat air capacitor, whose air gap was d₁ = 0.5 mm (0.0005 m), the surface of the capacitor’s cover was A = 18.8 cm² (0.001 88 m²). The capacitance of the flat air capacitor was calculated from formula (1).

\[
\frac{1}{C_a} = \frac{d_1}{\varepsilon_0 \cdot \varepsilon_1 \cdot A}.
\]
The capacitance of a flat capacitor with a dielectric is suitably for individual dielectrics; micanite $C_d = 41.6 \, \text{pF}$, glass $C_d = 97.1 \, \text{pF}$, Kapton foil $C_d = 582.3 \, \text{pF}$. The largest capacitance with dielectric was obtained for Kapton foil due to the low dielectric thickness $d_2 = 0.1 \, \text{mm}$. However, the lowest capacity was obtained for the micanite dielectric material $C_d = 41.6 \, \text{pF}$, because it has a dielectric constant $\varepsilon = 3$, and a tenfold greater thickness of 1.0 mm compared to the Kapton foil. The total reactor capacity $C_t$ was calculated according to the formula (3).

$$C_t = \frac{1}{C_a} + \frac{1}{C_d}.$$
The total reactor capacity of the plasma reactor with glass dielectrics was calculated according to formula (3).

\[
C_{t(glass)} = C_a + \frac{1}{C_d} = \frac{1}{33.3 \text{ pF}} + \frac{1}{97.1 \text{ pF}}
\]

\[
C_{t(glass)} = 24.8 \text{ pF.}
\]

The total reactor capacity \( C_t \) for micanite dielectric and Kapton foil was calculated analogously to the total volume of the reactor with glass dielectric \( C_{t(glass)} \). The total reactor capacity \( C_t \) for the micanite dielectric was \( C_{t(mica)} = 18.5 \text{ pF} \), for the Kapton insulation foil the total capacity \( C_{t(Kapton)} = 31.5 \text{ pF} \).

The operation of the plasma reactor is related to the capacity and the ignition voltage of the \( V_{min} \) discharge. Two dielectrics with similar thicknesses of micanite and glass were selected for the comparative analysis of \( V_{min} \) capacity and voltage. Analysis of Lissajous figures allowed to determine the ignition voltage for individual dielectrics. The calculated ignition voltage from the Lissajous figure shown in figure 5(a) for the glass dielectric was \( V_{min} = 1200 \text{ V} \), for the dielectric the micanite was \( V_{min} = 2400 \text{ V} \), figure 6(a). From the analysis of the capacity and ignition voltage calculations for individual dielectrics, the relation was visible, the higher the ignition voltage \( V_{min} \), the smaller the total capacity \( C_t \). Results of calculations and dependencies for individual dielectrics; glass dielectric \( V_{min} = 1200 \text{ V} (C_{t(glass)} = 24.8 \text{ pF}) \), dielectric micanite \( V_{min} = 2400 \text{ V} (C_{t(mica)} = 18.5 \text{ pF}) \). The \( V_{min} \) voltage for the micanite dielectric was twice as high as that obtained for the glass dielectric. The calculated capacitance \( C_d \) for both dielectrics was also compared to perform a full \( V_{min} \) capacity and ignition voltage analysis. Capacity \( C_d \) for a glass dielectric was \( C_{d(glass)} = 97.1 \text{ pF} (V_{min} = 1200 \text{ V}) \) was more than twice the \( C_d \) capacity calculated for the dielectric micanit \( C_{d(mica)} = 41.6 \text{ pF} (V_{min} = 2400 \text{ V}) \), it was almost
proportional to the increase voltage $V_{\text{min}}$. This confirms the dependence the smaller the capacity, the higher the ignition voltage $V_{\text{min}}$ (twice the smaller capacity $C_d$ causes a double increase in voltage $V_{\text{min}}$).

5. Conclusion

From the presented analysis of the experimental results of the plasma reactor with two mesh electrodes with mesh size of $0.3 \times 0.3 \text{ mm}^2$ and solid dielectrics; glass, micanite and insulating foil Kapton can be concluded that the concentration and efficiency of ozone generation are influenced by the dielectric constant $\varepsilon$, the dielectric thickness and the length of the discharge gap. Changing the dielectric type affects the total capacity of the $C_t$ reactor and the $C_d$ dielectric capacity. Changing the dielectric thickness also directly affects the total reactor capacity as shown in the results analysis.

The use of Kapton foil allows for the highest concentration of ozone during experimental investigations. A plasma reactor with a Kapton foil dielectric has the largest total capacity of $C_{t(\text{Kapton})} = 31.5 \text{ pF}$, which affects directly the volume of the load, power and thus the generation of ozone. The smallest reactor capacity was obtained in the presence of a micanite dielectric for which the total reactor capacity was $C_{t(\text{mican})} = 18.5 \text{ pF}$. Differences in total reactor capacities obtained for individual dielectrics translate directly into the concentration of ozone and the efficiency of its generation. Changes in total volume and concentration for micanite and Kapton foil dielectric are almost proportional to mutual changes. The decrease in the reactor capacity with the micanite dielectric was almost 50% lower than the total.

\begin{table} 
\centering
\begin{tabular}{|l|c|c|c|c|c|}
\hline
Dielectric & Voltage range (V) & Ignition voltage (V) & Maximum power (W) & Concentration O$_3$ (g O$_3$ m$^{-3}$) & Maximum generation efficiency O$_3$ (g O$_3$ kWh$^{-1}$) \\
\hline
Glass & 3020 ÷ 13 200 & 1200 & 1.91 & 0.08 ÷ 5.15 & 87.18 \\
Micanite & 4510 ÷ 13 900 & 3210 & 1.28 & 0.04 ÷ 2.70 & 82.88 \\
Kapton foil & 2360 ÷ 8270 & 1040 & 2.14 & 0.07 ÷ 9.30 & 142.45 \\
\hline
\end{tabular}
\caption{Measurement results for mesh electrodes size 0.3 \times 0.3 mm$^2$ and 0.5 mm discharge gap.}
\end{table}
capacity obtained for the ozone generators with a Kapton foil dielectric. The same relationship applies to the concentration of ozone but both dielectrics. Unfortunately, the use of Kapton insulating foil carries a high probability of damaging the dielectric. The insulating Kapton foil is a material that is not resistant to mechanical damage and, above all, it undergoes aging under the influence of ozone/discharges in the discharge gap. When choosing a dielectric, in addition to parameters such as the concentration and efficiency of ozone generation that were obtained for a given dielectric, the safety and failure-free operation of the reactor should also be taken into account. The innovative construction of the reactor use of two mesh electrodes, smooth change length of discharge gap and others parameters described in the manuscript, allows to obtain a similar efficiency of ozone production at a frequency 50 Hz, to industrial ozone generators (power supply frequencies much above 50 Hz).

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