Influence of the solid dielectric over the electric field from the ozone cell gap with double dielectric barrier

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Abstract. The distilled water has the advantage of high value dielectric constant (Ɛ = 81) in relation to ceramic glass materials, currently used for constructing the dielectric barrier. It was necessary to build a thin-walled enclosure of solid insulating material that contain distilled water to achieve a dielectric barrier. This was necessary to avoid exposing the liquid to the direct action of ozone. Dielectric permittivity of the solid dielectric material and the thickness of these walls have diminished the value of the electric field form the gaseous gap of the ozone cell compared to the case with the dielectric barrier from distilled water. The author of this work deduced theoretical relationships that express the values of the electric field intensity in the gap of the cell with two dielectrics and compared them with similar relationships of the intensity of the electric field from the gap of the ozone cell with one dielectric. In this work the author presenting experimental results which confirm the theoretical deducting regarding the use of the solid dielectric as enclosure for the liquid dielectric.

1. Introduction
Generating ozone (O₃) by the action of an intense electric field on air or oxygen is the most common method to produce ozone. Air or oxygen is generic called “working gas”. Ionization processes occurring in the working gas cause ozone, as a result of the action of the intense electric field. The process of the generating ozone by the action of an intense electric field over air or oxygen is called dielectric barrier discharge, and the device where the process takes place is called dielectric barrier discharge cell (DBDC) or ozone cell.

Ozone cells (Figures 1a, 1b) are composed of a layer of insulating material (dielectric barrier) with high dielectric strength positioned between two plane parallel electrodes or coaxial cylindrical electrodes. Between the dielectric layer and one of the electrodes is an empty space (gaseous gap) by circulating the working gas during exposure to electric field action. High dielectric strength prevents destructive breakdown to the action of the intense electric field generated between the electrodes of the ozone cell when they are powered with alternative high value voltage (5 – 30 kV).

The insulator used in construction of the ozone cell is a ceramic glass material which has the disadvantage of a low dielectric relative permittivity (Ɛᵢ) situated in the range of 8 ÷ 12 but it is resistant to mechanical shocks and high temperatures [1]. Electric field strength in the gap of the ozone cell is dependent by the permittivity of the dielectric barrier.
Figure 1a. Ozone cell with plane parallel electrodes

Figure 1b. Ozone cell with coaxial cylindrical electrodes

2. Ozone cells with double dielectric barrier (liquid and solid)
The main disadvantage of the ceramic glass materials, the low dielectric constant, can be removed using a dielectric liquid with high permittivity, distilled water, which has dielectric constant 81.

In this case dielectric barrier is composed of a liquid material which does not have its own form but can occupy any volume.

Since the dielectric barrier size and its position in relation to the electrodes have a very important role in the functioning of the DBDC, it is required creating a insulating a insulating solid enclosure that contains liquid insulator with high dielectric constant.
Consequently, the dielectric barrier will consist of three layers: two layers of the solid dielectric which contain a layer of the dielectric liquid.

This type of the barrier is called by the author double dielectric barrier. The solid layers have a technological role, to give an adequate shape to the dielectric liquid layer, and to put this layer in a properly position into the cell.

These layers affect the electric field strength in the gap and in the all others layers of the dielectric barrier. The dielectric barrier shape depends by the type of the cell electrodes. Figures 2 and 3 show the schematic diagrams of the dielectric barrier discharge cells.

In the following the theoretical relationships of the electric field intensity in the gap and in the layers of the dielectric barrier will be deducted for a cell with the plane parallel electrodes and a cell with coaxial cylindrical electrodes.

2.1. Dielectric barrier discharge with plane parallel electrodes (Figure 4)

The cell consists of two metallic plane electrodes with rectangular shape and negligible thickness parallel between them and a plane insulating layer which is the dielectric barrier.

The geometrical characteristics of the cell are:

- the distance between electrodes (d), the length (L) and width (l) of the electrodes (Figures 2 and 4);
- the thicknesses of the insulating layers forming the dielectric barrier the first solid layer (d_{21}), the liquid dielectric layer (d_{31}), the second solid layer (d_{22}) and thickness of the gap (d_{1}) (Figure 4);
- dielectric constant of: the gap (\varepsilon_{1}), the solid dielectric layers (\varepsilon_{2}), the liquid dielectric layer (\varepsilon_{3}).

The dielectric barrier is made up of two solid dielectric layers of the same material between these layers there being layer liquid with the permittivity greater than the solid material. Figure 4 shows a schematic diagram of the cell with plane parallel electrodes where are illustrated the main geometrical features of the cell.
DBDC can be removed electrically as a capacitor with three dielectrics and four layers. One of dielectrics is the working gas flowing through the gap and the others two are constituted of the dielectric barrier (the solid and liquid insulator).

We shall deduce the expressions of the electric field strength in the layers of the cell in the assumption that the value of the electric field strength outside the cell is zero and in a point inside the DBDC is [2]:

\[ E = \frac{\rho}{\varepsilon} \]  

(2.1)

\( \rho \) – the surface density on the surface of the electrodes  
\( \varepsilon \) – the dielectric constant of the medium in which the field is calculated

The values of the electric fields intensity into the four dielectric layers are:

\[ E_1 = \frac{\rho}{\varepsilon_1} \]  

(2.2)

\[ E_{21} = \frac{\rho}{\varepsilon_2} \]  

(2.3)

\[ E_3 = \frac{\rho}{\varepsilon_3} \]  

(2.4)

\[ E_{22} = \frac{\rho}{\varepsilon_2} \]  

(2.5)
E_1 – the electric field strength in the gap
E_{21} – the electric field strength in the solid dielectric (the layer 1)
E_3 – the electric field strength in the dielectric liquid
E_{22} – the electric field strength in the solid dielectric (the layer 2)
ρ – the surface density on the surface of a plane electrode is considered constant.

The field lines are perpendicular line segments on the surface of the electrodes but in the simplifying hypothesis which we assume into a real cell the expression of the electric field intensity in a point inside the dielectric barrier discharge cell is different from the expression (2.1) and the field lines are curve segments. The curvature of the field lines toward the edge of the electrodes increases (edge effect).

Into a real cell to minimize the edge effect must be meet the conditions:

\[ d \ll l \ , \ d \ll L \] (2.6)

We can write the equation between parameters d_1, d_{21}, d_3, d_{22} (Figure 4):

\[ d = d_1 + d_{21} + d_3 + d_{22} \] (2.7)

The relationship of the voltage between the two electrodes on a certain field line (line segment) is:

\[ d = E_1 \cdot d_1 + E_{21} \cdot d_{21} + E_3 \cdot d_3 + E_{22} \cdot d_{22} \] (2.8)

We will express the values of the electric fields intensity E_1, E_{21}, E_3, E_{22}, as a function of the voltage U the dielectric constants \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \), the geometrical parameters d_1, d_{21}, d_3, d_{22}, using relationships (2.2) ÷ (2.5):

\[ E_1 = \frac{U \cdot \varepsilon_2 \cdot \varepsilon_3}{\varepsilon_2 \cdot \varepsilon_3 \cdot d_1 + \varepsilon_1 \cdot \varepsilon_3 \cdot (d_{21} + d_{22}) + \varepsilon_1 \cdot \varepsilon_2 \cdot d_3} \] (2.9)

\[ E_{21} = E_{22} = \frac{U \cdot \varepsilon_1 \cdot \varepsilon_3}{\varepsilon_2 \cdot \varepsilon_3 \cdot d_1 + \varepsilon_1 \cdot \varepsilon_3 \cdot (d_{21} + d_{22}) + \varepsilon_1 \cdot \varepsilon_2 \cdot d_3} \] (2.10)

\[ E_3 = \frac{U \cdot \varepsilon_1 \cdot \varepsilon_2}{\varepsilon_2 \cdot \varepsilon_3 \cdot d_1 + \varepsilon_1 \cdot \varepsilon_3 \cdot (d_{21} + d_{22}) + \varepsilon_1 \cdot \varepsilon_2 \cdot d_3} \] (2.11)

The expression of the intensity of the electric field E_1 (2.9) using equation (2.7) will be brought to the form:

\[ E_1 = \frac{U}{d} \cdot \frac{\varepsilon_3 \varepsilon_2}{\frac{1}{\varepsilon_1} + \left( \frac{\varepsilon_3 - 1}{\varepsilon_1} \right) \frac{d_1}{d} + \left( \frac{\varepsilon_3 - 1}{\varepsilon_2} \right) \frac{d_{21} + d_{22}}{d}} \] (2.12)

From relationships (2.10) and (2.11) we obtain relations for the intensity of the electrical fields in both solid and liquid dielectrics (E_{21}, E_{22}, E_3)

\[ E_{21} = E_{22} = \frac{U}{d} \cdot \frac{\varepsilon_3 \varepsilon_2}{\frac{1}{\varepsilon_1} + \left( \frac{\varepsilon_3 - 1}{\varepsilon_1} \right) \frac{d_1}{d} + \left( \frac{\varepsilon_3 - 1}{\varepsilon_2} \right) \frac{d_{21} + d_{22}}{d}} \] (2.13)

\[ E_3 = \frac{U}{d} \cdot \frac{1}{\frac{1}{\varepsilon_1} + \left( \frac{\varepsilon_3 - 1}{\varepsilon_1} \right) \frac{d_1}{d} + \left( \frac{\varepsilon_3 - 1}{\varepsilon_2} \right) \frac{d_{21} + d_{22}}{d}} \] (2.14)
2.2. **Dielectric barrier discharge cell with coaxial cylindrical electrodes with double dielectric barrier**

This type of the cell (Figure 5) has two coaxial cylinders with negligible thickness constituting cell electrodes. Dielectric barrier is composed by three cylindrical layers: a liquid layer between two solid layers. The geometrical characteristics of the cell with coaxial cylindrical electrodes are:

- \( r_1 \) – the outer electrode radius;
- \( r_{21} \) – the radius of the first dielectric layer of the solid dielectric with the permittivity \( \varepsilon_2 \);
- \( r_3 \) – the radius of the surface of the dielectric layer separating the liquid (dielectric with the permittivity \( \varepsilon_3 \) and the first solid dielectric layer (dielectric with the permittivity \( \varepsilon_2 \));
- \( r_{22} \) – the radius of the surface of separation between the second dielectric layer of the solid and liquid dielectric layer (dielectric with the permittivity \( \varepsilon_2 \));
- \( r_4 \) – the radius of the inner electrode of the cell;
- \( L \) – the length of the cell electrodes (Figure 3).

We deduct mathematical relations expressing intensities of the electric field in the gap and the solid dielectric liquid deducted in the simple assumption that the intensity of the electric field \( E \) in a point outside the cell is zero and inside the cell is given by [3], [4]:

\[
\vec{E} (r) = \frac{\rho}{2 \cdot \pi \cdot \varepsilon \cdot \vec{r}} \cdot \left( r_{21} < r < r_1 \right)
\]  

(2.15)

\( \rho \) -the surface charge density on the electrodes cell (it is considered constantly in this case)

\( \varepsilon \) –the dielectric constant of the environment

\( r \) – the radius of the cylindrical surface where the point is situated

![Diagram of the ozone cell with coaxial cylindrical electrodes (dielectric barrier solid and liquid)](image)

**Figure 5.** The ozone cell with coaxial cylindrical electrodes (dielectric barrier solid and liquid)

Electric field lines are line segments which overlap with the radius of the cylinders if we idealize the cell. In the real case the field lines are curve segments. The curvature of the field lines increases as approaching the electrode edges (edge effect). To minimize edge effect in a real cell, it must be fulfilled the relationship:

\[
\left( r_1 \ll L \right)
\]  

(2.16)

Ozone cell can be assimilated to a capacitor with coaxial cylindrical electrodes dielectric having four layers. Voltage U applied to the electrodes of the cell is distributed on each dielectric separately:
\[
U = U_1 + U_{21} + U_3 + U_{22}
\]  \hspace{1cm} (2.17)

- \(U_1\) – the voltage drop across the gap
- \(U_{21}\) – the voltage drop across the first solid dielectric layer
- \(U_3\) – the voltage drop across the layer of the dielectric liquid
- \(U_{22}\) – the voltage drop on the second layer of the solid dielectric

Voltage drop \(U\) caused by the dielectric field \(E_1\) in the space between two points a and b is defined by the relationship \([3], [4]\):

\[
U = \int_a^b \vec{E} \cdot d\vec{s}
\]  \hspace{1cm} (2.18)

Given the relationship (2.2.4) the relationship (2.2.3) becomes:

\[
U = \int_{r_1}^{r_2} \vec{E}_1 \cdot d\vec{s} + \int_{r_2}^{r_3} \vec{E}_2 \cdot d\vec{s} + \int_{r_3}^{r_4} \vec{E}_3 \cdot d\vec{s} + \int_{r_4}^{\infty} \vec{E}_4 \cdot d\vec{s}
\]  \hspace{1cm} (2.19)

- \(E_1\) – the electric field intensity of the gap
- \(E_{21}\) – the electric field intensity of the first solid dielectric layer (the layer 1)
- \(E_3\) – the electric field intensity in the dielectric liquid
- \(E_{22}\) – the electric field intensity of the second solid dielectric layer (the layer 2)

Given the relationships (2.15) relationship (2.19) becomes:

\[
U = \int_{r_1}^{r_2} \frac{\rho}{2 \cdot \pi \cdot \varepsilon_1 \cdot r} \cdot d\vec{s} + \int_{r_2}^{r_3} \frac{\rho}{2 \cdot \pi \cdot \varepsilon_2 \cdot r} \cdot d\vec{s} + \int_{r_3}^{r_4} \frac{\rho}{2 \cdot \pi \cdot \varepsilon_3 \cdot r} \cdot d\vec{s} + \int_{r_4}^{\infty} \frac{\rho}{2 \cdot \pi \cdot \varepsilon_4 \cdot r} \cdot d\vec{s}
\]  \hspace{1cm} (2.20)

Calculating the integrals of the equation (2.20) we get:

\[
U = \frac{\rho}{2 \cdot \pi} \left( \frac{1}{\varepsilon_1} \ln \frac{r_1}{r_2} + \frac{1}{\varepsilon_2} \ln \frac{r_2}{r_3} + \frac{1}{\varepsilon_3} \ln \frac{r_3}{r_4} + \frac{1}{\varepsilon_4} \ln \frac{r_4}{\infty} \right)
\]  \hspace{1cm} (2.21)

\[
\ln \frac{r_1}{r_4} = \ln \frac{r_1}{r_2} + \ln \frac{r_2}{r_3} + \ln \frac{r_3}{r_4} + \ln \frac{r_4}{\infty}
\]  \hspace{1cm} (2.22)

Given the relationship (2.15) the expression of the electric field intensity in a point on the cylindrical surface with the radius \(r\) for the gap (\(E_1\)) is given by the expression:

\[
\vec{E}_1(r) = \frac{\rho}{2 \cdot \pi \cdot \varepsilon_1 \cdot \sqrt{r}}\cdot \left( r_{21} < r < r_1 \right)
\]  \hspace{1cm} (2.23)

Since the field lines \(E_1\) are overlapped with radii \(r_{21}, r_1\) the relationship (2.23) can also be written as scalar form:

\[
E_1(r) = \frac{\rho}{2 \cdot \pi \cdot \varepsilon_1 \cdot r}\cdot \left( r_{21} < r < r_1 \right)
\]  \hspace{1cm} (2.24)

We deduce from the relationships (2.21), (2.22), (2.23) the expression:

\[
E_1(r) = \frac{\varepsilon_3}{\varepsilon_1} \cdot \frac{U}{r \cdot \ln \frac{r_1}{r_4} \left[ 1 + \left( \frac{\varepsilon_3}{\varepsilon_1} - 1 \right) \cdot \frac{\ln \frac{r_1}{r_2} + \ln \frac{r_2}{r_3} + \ln \frac{r_3}{r_4}}{\ln \frac{r_1}{r_4}} \right]}
\]  \hspace{1cm} (2.25)
We denote:

\[ E_0(r) = \frac{U}{r \cdot \ln \frac{r_1}{r_4}} \]  (2.26)

The expression (2.26) is the relationship of the electric field inside the two coaxial cylindrical metal electrodes located in a medium with dielectric constant value equals the unity.

The expression (2.25) becomes:

\[ E_1(r) = E_0 \cdot \frac{\varepsilon_3}{\varepsilon_1} \cdot \left( 1 + \left( \frac{\varepsilon_3}{\varepsilon_1} - 1 \right) \cdot \ln \frac{r_1}{r_4} + \left( \frac{\varepsilon_3}{\varepsilon_2} - 1 \right) \cdot \ln \frac{r_1 + r_2}{r_3 + r_4} \right) \]  (2.27)

The intensities of the electric fields \( E_{21}, E_3, E_{22} \) are:

\[ E_{21}(r) = \frac{U}{r \cdot \ln \frac{r_1}{r_4}} \cdot \frac{\varepsilon_3}{\varepsilon_2} \cdot \left( 1 + \left( \frac{\varepsilon_3}{\varepsilon_1} - 1 \right) \cdot \ln \frac{r_1}{r_4} + \left( \frac{\varepsilon_3}{\varepsilon_2} - 1 \right) \cdot \ln \frac{r_1 + r_2}{r_3 + r_4} \right) \]  (2.28)

\[ E_3(r) = \frac{U}{r \cdot \ln \frac{r_1}{r_4}} \cdot \frac{1}{\frac{r_1}{r_4}} \cdot \left( 1 + \left( \frac{\varepsilon_3}{\varepsilon_1} - 1 \right) \cdot \ln \frac{r_1}{r_4} + \left( \frac{\varepsilon_3}{\varepsilon_2} - 1 \right) \cdot \ln \frac{r_1 + r_2}{r_3 + r_4} \right) \]  (2.29)

\[ E_{22}(r) = \frac{U}{r \cdot \ln \frac{r_1}{r_4}} \cdot \frac{\varepsilon_3}{\varepsilon_2} \cdot \left( 1 + \left( \frac{\varepsilon_3}{\varepsilon_1} - 1 \right) \cdot \ln \frac{r_1}{r_4} + \left( \frac{\varepsilon_3}{\varepsilon_2} - 1 \right) \cdot \ln \frac{r_1 + r_2}{r_3 + r_4} \right) \]  (2.30)

3. Experimental results

Experimental verification of the theoretical relationships deduced above was done in the laboratory of the intense electric fields of Electrical Engineering Faculty of the Technical University of Cluj-Napoca.
The imagines presented in the Figures 6a and 6b show the experimental bench where was mounted the dielectric barrier cell. This cell was powered to a sinusoidal voltage variable frequency of 50 Hz. Determining the values of the electric field intensity was made indirectly by measuring the voltage at which the ionization processes are initiated in the gap ($U_{ion}$) [5].

The ionization processes is manifested by the appearance of thread-like trails that emit violet light accompanied by a specific low frequency noise [6]. The both phenomena become more intense with increasing voltage (Figures 7a, 7b).

![Figure 6a. Experimental bench (front view)](image)

![Figure 6b. Frontal view of the DBDC electrodes](image)

![Figure 7a. Experimental bench (front view)](image)

![Figure 7b. Frontal view of the DBDC electrodes](image)

![Figure 8. Representation of the experimental results (d = 20 mm)](image)
In DBDC the distance between electrodes (d) and the thickness gap (d₁) were maintained constantly. It was changed thickness of the insulating layer (d₁₁ and d₂₂) and thus the thickness of the dielectric liquid (d₁). Every measurement was made with identical thickness layers (d₂₁ = d₂₂). The material used for the solid layer was polyethylene. The supply voltage was gradually increased and the values of starting ionization process was noted. Then using the relationship of the electric field \( E₁ \) deduced above (2.26) was calculated for each case, the electric field intensity in the gap of the cell.

The values of the electric field intensity (\( E₁ \)) were located around value of 3.5 kV/mm. Then they were plotted in a chart the experimental measurements of the ionization voltage (Figure 8) and the theoretical values calculated were plotted in the chart shown in Figure 9 calculated for a value of the field \( E₁ = 3.5 \text{kV/mm} \).

Measurements were made on a cell with plane parallel electrodes having the distance of 20 mm between the electrodes, the dielectric liquid used was distilled water and the enclosure was made by polyethylene with the dielectric constant \( \varepsilon₂ = 3.2 \).

In the diagram shown in Figure 8 is observed that the experimental data measured at the start of the ionization phenomena of the working gas are grouped around a straight line plotted for each set of the measured values.

The straight line plotted in the Figure 8 (highlighted in the chart with the notation “linear \( d₁ = 1\text{mm} \)” for example) coincides with the graphical representation of the ionization voltage \( U_{\text{ion}} \) values for the electric field intensity \( E₁ = 3.5 \text{kV/mm} \) using the equation (2.26). The difference between data measurements and theoretical calculations fall into errors of the measuring apparatus and of the measurement methods.

For experimental verification has been chosen a cell with plane parallel electrodes because it allows a good view of the luminous phenomena taking place in the gaseous gap but also because the theoretical value of the electric field in the gap is constantly in every point.

4. Conclusions:
- the expressions of the electric fields intensity in the cell with plane parallel electrodes and the cell with coaxial cylindrical electrodes have the same form;
- the electric field intensity in the gap of the two types of the cells with double dielectric barrier have maximum values when \( \varepsilon₂ = \varepsilon₃ \) or \( d₂₁ \) and \( d₂₂ \) are zero (for the cell with plane parallel electrodes) and \( \varepsilon₂ = \varepsilon₃ \) or \( r₂₁ \cdot r₂₂ \cdot r₃ \cdot r₄ = 1 \) (for the cell with coaxial cylindrical electrodes);
it is recommended to reduce to a minimum the thickness of walls of the cell (d_{21} and d_{22} must tend to zero for cell with plane parallel electrodes and the reports \( r_{21}/r_3 \) and \( r_{22}/r_4 \) must tend to unity for the cell with coaxial cylindrical electrodes).

References

[1] Suarasan I 2000 Generarea si utilizarea ozonului, Editura ETA Cluj-Napoca, Romania
[2] Kogelschatz U 2003 Dielectric – barrier Discharges: Their History Discharge Physics and Industrial Applications, Plasma Chemistry and Plasma Processing 23(1)
[3] Ciupa R 2006 Bazele electrotehnicii: teorie si aplicatii, Vol 1 and 2, Casa Cartii de Stiinta, Cluj-Napoca, Romania
[4] Sora C 1982 Bazele Electrotehnicii, Editura Didactica si Pedagogica, Bucuresti, Romania
[5] Kogelschatz U, Eliasson B and Egli W 1997 Dielectric Barrier Discharges. Principle and Applications, J. Phys IV France 7 (1997) Colloque C4, Supplement au Journal de Physique III
[6] Samoilovich V G, Gibalov V I and Kozlov K V 1997 Physical Chemistry of the Barrier Discharge (in Russian) Moscow State University (1989), English translation: J. P. F. Conrads, f. Leipold, (Eds), DVS – Verlag GmbH, Dusseldorf, Germany