Factors that increase the electric field of the dielectric barrier ozone generators

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Abstract. The dielectric barrier discharge cell (DBDC), also called ozone cell, is the main component of the ozone generators widely used. When the cell is powered with a high voltage value (> 5 kV) in the dielectric gas, arises a high intensity electric field that influences ozone generation processes by silent discharge also called dielectric barrier discharge. The intensity of the electric field depends by a number of factors such as the constructive form of the cell, the cell sizes, the value and the waveform of the supply voltage, the type of insulators used as dielectric barrier. The insulators which constituting the dielectric barrier, influence the intensity of the electric field through the dielectric constant of the liquid or solid shows the values of intensity electrical fields from ozone cells, with plane electrodes and ozone cells with cylindrical electrodes. The paper presents a graphic variation of the electric field from the gap and the dielectric barrier of cells with plane electrodes and cylindrical collinear electrodes. Experimental research highlights current-voltage characteristic for several types of dielectrics. Distilled water was highlighted as dielectric with the best results.

1. Introduction
For applications using ozone (O₃) are used generators (ozonizers) which have capabilities very small and small (micro and miniozonizers). These are composed of one or more DBDCs. Ozone cell consists of two electrodes of different shapes, separated by a space, partially occupied by a solid dielectric. Solid dielectric prevents discharge in the gap. A high voltage applied between the electrodes of DBDC, causes ionization processes into the gaseous gap which finally lead to ozone generation.

Generators of ozone are made up of cells with plane parallel and coaxial cylindrical electrodes [1], [2]. Ionization processes in the gaseous gap are heavily depended by the value of the electric field that arises when the cell electrodes are supplied with high voltage. In its turn, the electric field depends by many factors. The increase of the electric field into the gap cell leads to increasing the amount of generated ozone [3].

2. Calculation of intensity electric fields of the ozone cells
Dielectric barrier discharge cell (DBDC) is an enclosure having a form by rectangular parallelepiped or right cylinder bounded by two electrodes. The electrodes are separated to each other by a space occupied partially by a solid dielectric layer. Unoccupied volume between the electrodes and solid dielectric (gaseous or discharge gap), is used for moving the working gas. The electrodes are either two conductive plane parallel or coaxial cylinders [3], [4].
In Figures 1a, 1b are shown schematic diagrams of a cell with plane parallel electrodes and a cell with coaxial cylindrical electrodes. To develop theoretical considerations, we go from following conditions that allow neglecting edge effects:

- the electric field is uniform inside the cells;
- the value of the electric field intensity, outside the cells is zero;
- charge density, $\rho$, is constantly and evenly distributed over the entire surface of the electrodes;
- linear dimensions of electrodes (length and width) are much higher compared to the distance between them.

To properly size an ozone cell there is important to know the intensities of the electric fields into the solid dielectric layer and into the gap which depend on the geometrical dimensions of the cell and the voltage value.

2.1. The ozone cell with plane parallel electrodes (Figure 1a)

The intensity of the electric field inside a gaseous gap of a cell with plane parallel electrodes is given by the following relationship [3]:

$$ E_1 = \frac{\varepsilon_2 \cdot U}{\varepsilon_1 \cdot d_2 + \varepsilon_2 \cdot d_1} $$

(E1 - electric field intensity of the discharge gap,
$\varepsilon_1$ - permittivity of the working gas (air or oxygen),
$\varepsilon_2$ - permittivity of the solid dielectric,
d1 - gaseous gap thickness,
d2 - solid dielectric thickness)

$$ E_2 = \frac{\varepsilon_1 \cdot U}{\varepsilon_1 \cdot d_2 + \varepsilon_2 \cdot d_1} $$

(E2 - electric field strength in the solid dielectric
We can write the following

$$ d = d_1 + d_2 $$

(2.3)
\[ E_1 = \frac{\varepsilon_2 U}{\varepsilon_1 \cdot d \left( 1 + \left( \frac{\varepsilon_2}{\varepsilon_1} - 1 \right) \frac{d}{d_1} \right)} = \frac{U}{d} \cdot \frac{\varepsilon_2 / \varepsilon_1}{1 + \left( \frac{\varepsilon_2}{\varepsilon_1} - 1 \right) \frac{d}{d_1}} \cdot \frac{\varepsilon_2 / \varepsilon_1}{1 + \left( \frac{\varepsilon_2}{\varepsilon_1} - 1 \right) \frac{d}{d_1}} \quad (2.4) \]

\[ E_2 = \frac{\varepsilon_1 U}{\varepsilon_1 \cdot d \left( 1 + \left( \frac{\varepsilon_2}{\varepsilon_1} - 1 \right) \frac{d}{d_1} \right)} = \frac{U}{d} \cdot \frac{1}{1 + \left( \frac{\varepsilon_2}{\varepsilon_1} - 1 \right) \frac{d}{d_1}} \cdot \frac{1}{1 + \left( \frac{\varepsilon_2}{\varepsilon_1} - 1 \right) \frac{d}{d_1}} \quad (2.5) \]

\[ E_0 = \frac{U}{d} \quad (2.6) \]

In relationships (2.4), (2.5), (2.6) appears expression \( U/d \) noted \( E_0 \) having the electric field dimension.

The dependence of the electric field intensity (\( E_2 \)) as a function of permittivities ratio – \( (E_0 = 1) \)

**Figure 2a.** Graphic representation of the electric field intensity (\( E_1 \)) in the gap of DBDC with planar electrodes \( (E_0 = 1) \)
The dependence of the electric field intensity ($E_2$) as a function of the permittivities ratio — ($E_0 = 1$)

Figure 2b. Graphic representation of the electric field intensity ($E_2$) in the gap of DBDC with planar electrodes ($E_0 = 1$)

The authors of this paper define this report (2.6), the electric field strength inside the DBDC when whole space between the electrodes is occupied by an insulator with relative permittivity equal with unity. In Figures 2a and 2b there are plotted the variation of electric field intensities in the gap, and in the dielectric barrier as a function of $\varepsilon_2/\varepsilon_1$ (relationships (2.4), (2.5) for several values of $d_1$ (value of $d$ is considered a constant parameter). The value of the relationship $E_0 = U/d$ is equal with unity in these representations.

Conclusions:
- in any point inside DBDC the electric field strength is independent of the coordinates of the point, and it is proportional with the supply voltage $U$ of the cell electrodes;
- the value of the electric field in the gaseous gap differs from the value of the electric field intensity in the dielectric;
- the electric field strength in the gap ($E_1$) increases with the ratio $\varepsilon_2/\varepsilon_1$ and the electric field int the dielectric decreases with the same ratio ($d_1/d$ is maintained constantly);
- the variations of the electric field strength in the gap and the electric field in the dielectric occur after a nonlinear law;
- the intensity of the electric fields in the gap and in the dielectric decreases when $d_1/d$ increases ($\varepsilon_2/\varepsilon_1$ is maintained constantly).

2.2. The ozone cell with coaxial cylindrical electrodes (Figure 1b)
The ozone cell with coaxial cylindrical electrodes is composed of two coaxial cylindrical metal electrodes between which is a solid dielectric.

The geometrical parameters of the cell (Figure 1b and 3)
- $r_1$ - the radius of the outer cylinder
- $r_2$ - the radius of the cylindrical surface that separates the two dielectrics
- $r_3$ - the radius of the inner cylinder
- $l$ - the length of the ozone cell
Between \( r_1, r_2, r_3 \) there is the relationship:
\[
 r_3 < r_2 < r_1 \tag{2.7}
\]

The intensity of the electric field in the gap (\( E_1 \)) and the electric field intensity in the dielectric (\( E_2 \)) are:
\[
 E_1(r_{01}) = \frac{U}{r_{01}} \cdot \frac{\varepsilon_2}{\left( \varepsilon_1 \ln \frac{r_2}{r_3} + \varepsilon_2 \ln \frac{r_1}{r_2} \right)} \quad (r_2 < r_{01} < r_1) \quad [5] \tag{2.8}
\]

\( \varepsilon_1 \) – the permittivity of the gas (air or oxygen)
\( \varepsilon_2 \) – the permittivity of the solid insulator
\( r_{01} \) – the coordinate of a point in the gap where \( E_1 \) is calculated

\[
 E_2(r_{02}) = \frac{U}{r_{02}} \cdot \frac{\varepsilon_1}{\left( \varepsilon_1 \ln \frac{r_2}{r_3} + \varepsilon_2 \ln \frac{r_1}{r_2} \right)} \quad (r_3 < r_{02} < r_2) \quad [5] \tag{2.9}
\]

\( r_{02} \) – the coordinate of a point in the solid dielectric where \( E_2 \) is calculated

Between the rays \( r_1, r_2, r_3 \), we write the equation:
\[
 \ln \frac{r_1}{r_3} = \ln \frac{r_1}{r_2} + \ln \frac{r_2}{r_3} \tag{2.10}
\]

Expressing the values of \( E_1 \) and \( E_2 \) as functions of the \( \varepsilon_2/\varepsilon_1 \) and \( \ln(r_1/r_2)/\ln(r_1/r_3) \), the relationships (2.8) and (2.9) become:  

**Figure 3.** Schematic diagram of a DBDC with collinear cylindrical electrodes

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E_1(r_{01}) = \frac{U}{r_{01} \cdot \ln \frac{r_1}{r_3}} \left( \frac{\varepsilon_2/\varepsilon_1}{1 + \left( \frac{\varepsilon_2}{\varepsilon_1} - 1 \right) \cdot \ln \frac{r_2}{r_1} \cdot \ln \frac{r_1}{r_3}} \right) \quad (r_2 < r_{01} \leq r_1) \quad (2.11)

E_2(r_{02}) = \frac{U}{r_{02} \cdot \ln \frac{r_1}{r_3}} \left( \frac{1}{1 + \left( \frac{\varepsilon_2}{\varepsilon_1} - 1 \right) \cdot \ln \frac{r_2}{r_1} \cdot \ln \frac{r_1}{r_3}} \right) \quad (r_3 < r_{02} \leq r_2) \quad (2.12)

The dependence of the electric field intensity (E_1) as a function of the permittivities ratio – (E_0 = 1)

**Figure 4a.** Graphic representation of the electric field intensity (E_1) in the gap of the DBDC with cylindrical electrodes; E_01(r_{01}) = 1
Figure 4b. Graphic representation of the electric field intensity (E2) in the gap of the DBDC with cylindrical electrodes; E02(r01)=1

We denote by:

\[ E_0(r_{01}) = \frac{U}{r_{01} \cdot \ln(r_1/r_3)} \]  
\[ E_0(r_{02}) = \frac{U}{r_{02} \cdot \ln(r_1/r_3)} \] (2.13) (2.14)

Conclusions:
- the value of the electric field in the discharge gap and in the dielectric barrier is dependent by the coordinate where the point is considered;
- the value of the electric intensity in any point on a cylindrical surface of the radius \( r_{01}, r_{02} \) (Figure 3) is the same and coincides with the direction of the radius of the surface;
- the value of the electric field in the gap is lower than in dielectric;
- \( E_2/E_1 \) increases the electric field intensity in the gap and decreases the dielectric field strength for a given value of the ratio \( d/d_1 \);
- the growth of the \( d/d_1 \) lowers the electric field intensity in the gap and in the dielectric layer when the ratio \( E_2/E_1 \) is kept constantly.

3. Similarities between expressions of the electric field intensity of DBDC with plane parallel and coaxial cylindrical electrodes

Between relationships (2.4), (2.5), (2.11), (2.12) we can make a formal resemblance. In the following we write a general relationship of the intensities of the electric fields in the gap and in the dielectric barrier.

These relationships are not depended by the shape of the cell electrodes.
\[ E_1 = E_0 \cdot \frac{a}{(1 + (a-1) \cdot b)} \]  \hspace{1cm} (3.1)

\[ E_2 = E_0 \cdot \frac{1}{(1 + (a-1) \cdot b)} \]  \hspace{1cm} (3.2)

**Table 1.** The correspondence between relationships of a planar electrodes DBDC and a DBDC with cylindrical electrodes

| The DBDC with plane parallel electrodes | The DBDC with coaxial cylindrical electrodes | Obs. |
|----------------------------------------|------------------------------------------|------|
| 1 \[ E_1 = \frac{U}{d} \cdot \frac{\varepsilon_2/\varepsilon_1}{1 + (\varepsilon_2/\varepsilon_1 - 1) \cdot \frac{d_1}{d}} \] | \[ E_1(r_{01}) = \frac{U}{r_{01} \cdot \ln \frac{r_1}{r_3}} \cdot \frac{\varepsilon_2/\varepsilon_1}{1 + (\varepsilon_2/\varepsilon_1 - 1) \cdot \ln \frac{r_2}{\frac{r_1}{r_3}}} \] | \[ r_2 < r_{01} \leq r_1 \] |
| 2 \[ E_2 = \frac{U}{d} \cdot \frac{1}{1 + (\varepsilon_2/\varepsilon_1 - 1) \cdot \frac{d_1}{d}} \] | \[ E_2(r_{02}) = \frac{U}{r_{02} \cdot \ln \frac{r_1}{r_3}} \cdot \frac{1}{1 + (\varepsilon_2/\varepsilon_1 - 1) \cdot \ln \frac{r_2}{\frac{r_1}{r_3}}} \] | \[ r_3 < r_{02} \leq r_2 \] |
| 3 \[ E_0 = \frac{U}{d} \] | \[ E_0(r_{0(1,2)}) = \frac{U}{r_{0(1,2)} \cdot \ln (\frac{r_1}{r_3})} \] |
| 4 \[ d_1 \] | \[ \ln \frac{r_1}{r_2} \] |
| 5 \[ d_2 \] | \[ \ln \frac{r_2}{r_3} \] |
| 6 \[ d \] | \[ \ln \frac{r_1}{r_3} \] |
| 7 \[ \varepsilon_2/\varepsilon_1 \] | \[ \varepsilon_2/\varepsilon_1 \] | A |
| 8 \[ d_1/d \] | \[ \ln \frac{r_1}{\frac{r_1}{r_2}}/\ln \frac{r_1}{r_3} \] | B |

The terms of this relationship have different expressions as a function of the shape of the electrodes. Table 1 shows the similarities of the formal expressions of the parameters \( E_1, E_2, E_0, a, b, \) \((3.1), (3.2)\) regardless of the shape of the electrodes cells. Figures 2a, 2b, 4a, 4b suggests an upper limit of the values of the electric field intensity into the gap \( (E_i) \) when the expression \( \varepsilon_2/\varepsilon_1 \) tends to infinity. This value is given by the expression:

\[ E_1 = \frac{E_0}{b} \]  \hspace{1cm} (3.3)
Substituting the values of $b$ from Table 1 in the expression (3.3) we obtain the limit values for the electric field strength $E_1$ in the cell with plane-parallel electrodes:

$$E_1 = \frac{U}{d_1}$$  \hspace{1cm} (3.4)

The limit value of $E_1$ in the gaseous gap of the DBDC with coaxial cylindrical electrodes is:

$$E_1(r_{01}) = \frac{U}{r_{01} \cdot \ln(r_1/r_2)}$$  \hspace{1cm} (3.5)

The limit value of $E_2$ in the dielectric barrier of the DBDC when the value of the ratio $\varepsilon_2/\varepsilon_1$ tends to infinity is zero regardless of the shape of the electrodes.

4. Experimental results

For the experimental verification of the theoretical results derived in the above presentation the authors used as a dielectric the distilled water, the transformer oil, the acrylic resin, the ordinary glass, and the polyethylene. The experiments were achieved in the laboratory of the intense fields of the Faculty of Electrical Engineering of the Technical University of Cluj-Napoca.

The experimental bench (Figures 5a, 5b) contained a dielectric barrier discharge cell having two plane parallel electrodes with the following geometric dimensions: $L = 70$ mm (length), $l = 25$ mm (width), $d = 12$ mm (distance between the cell electrodes).

![Figure 5a. Experimental bench (front view)](image)

![Figure 5b. Frontal view of the DBDC electrodes](image)

The cell employed allowed experiments with solid or liquid dielectrics. In the frame of the experimental procedure values of the electric field into the gap was indirect determined by measuring the voltage value when the ionization processes started.

The voltage current characteristics was plotted for each dielectric employed, by increasing the voltage in the range of $0 – 20$ kV and measuring the current through the cell. The gas ionization phenomena were manifested by the appearance of a luminescent violet filaments between electrode and dielectric barrier, accompanied by a specific noise [5].

The light and the noise intensity were intensified when the voltage is progressively increased. The voltage value at which begins the process of the ionization is called ionization voltage ($U_{ion}$) kV and the value of the electric field into the gap $E_{ion}$ [kV/mm] is called ionization electric field. Using equation (2.1.4), the values of the electric field in the gaseous gap was calculated considering that the electric field intensity is constantly inside the cell. The air was used as working gas for experimental determinations. Ozone cell was powered with sinusoidal voltage of 50 Hz in range of $0 – 20$ kV. For every type of the dielectric was plotted more voltage-current characteristics [6] for several values gap ($d_i$) maintaining constantly distance value between electrodes.
Figure 6. The voltage current characteristics of a DBDC with dielectric barrier distilled water

Figure 6 shows graphic representations of voltage-current characteristics for distilled water ($\varepsilon = 81$), and transformer oil ($\varepsilon = 2.5$) for several values of $d_1$ keeping the value $d$ constant at 12 mm.

In the Figure 7 are represented voltage-current characteristics plotted when in DBDC was used distilled water, glass, polyethylene, acrylic resins, transformer oil. Table 2 contains voltage values $U_{\text{ion}}$ at which were ionization processes and calculated values of the electric field in the gaseous gap ($E_1$) for a discharge cell with plane parallel electrodes with the geometrical parameters: $L = 70$ mm, $l = 25$ mm, $d = 12$ mm, $d_1 = 1.5$ mm.

Figure 7. The voltage current characteristics for more type of dielectrics used as dielectric barrier

Electric field intensity $E_{\text{ion}}$ was calculated for dielectric constant of air: $\varepsilon_1 = 1.00059$. The calculated values of the dielectric field intensity $E_1$ in the discharge gap for each type of dielectric tend to $3.5kV/mm$ (Table 2). These values are influenced by the measurement process.
Table 2 - Ionization voltage of the air into the gap of the DBDC (d = 70 mm, d₁ = 1.5 mm)

| Type of the dielectric | ε₂  | U_{ion} [kV] | E_{ion} [kV/mm] |
|------------------------|-----|-------------|-----------------|
| 1 glass                | 5.5 | 9           | 3.45            |
| 2 transformer oil      | 2.5 | 13          | 3.33            |
| 3 distilled water      | 81  | 5.5         | 3.37            |
| 4 acrylic resin        | 3.5 | 11          | 3.38            |
| 5 polyethylene         | 2.9 | 12          | 3.39            |

5. Conclusions

- the expressions of the electric field intensity in the gap and in the dielectric barrier are not the same shape at a dielectric barrier discharge cell;
- the relationships of the electric field in the gap have the same shape but their coefficients are depended of the shape of electrodes (Table 2);
- value of the electric field intensity in the gap of the ozone cell and in the dielectric barrier proportionally increases with the supply voltage (U);
- electric fields values of a DBDC with plane parallel electrodes are independent of the coordinates of the point where they are calculated;
- into a DBDC with coaxial cylindrical electrodes the values of electric field intensity are dependent by coordinates of the point;
- rising the value of ε₂/ε₁ increases the value of the electric field in the gap, and decreases the value of the electric field intensity in the dielectric barrier for given value of d₁/d;
- rising the value ratio d₁/d for given values of ε₂/ε₁ decreases the electric field intensity in the gap and in the dielectric barrier;
- the distilled water may form a dielectric barrier for an ozone cell because its high value relative permittivity determines an intense electric field into the gap.

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