Electro-physical and plasma-chemical processes in a volume-surface barrier discharge in air for a joint application of a.c. and d.c. voltages

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Abstract. The volume-surface barrier discharge that appears in a three-electrode system in air is analyzed. It is shown that for frequency of the applied a.c. voltage 13.7 kHz and a d.c. voltage of the third electrode up to 10 kV there is a marked influence of the volume charge that appears in the gas gap above the surface discharge plasma layer, on the production of charged and chemically active species such as ozone.

Keywords: surface barrier microdischarges, ozone production, microdischarges, volume charge

1. Introduction

It is well known by now that barrier and surface barrier discharges can be used as a source of charged and chemically active products such as ozone. The devices with the surface discharge have certain advantages compared to the traditional barrier discharge arrangements, such as for instance an absence of the gas gap width influence on the discharge. Previous investigations [1, 2] have shown that in a so called three-electrode system it is possible to increase the surface discharge intensity and to increase the input of charged species into the gas gap compared to a traditional surface discharge two-electrode configuration.

In [3] a possible influence of the volume charge on the electric field in the gas gap has been discussed. The present contribution gives some new experimental results concerning the processes connected with joint application of an a.c. and d.c. voltages in a three-electrode system.

2. Experimental

All experiments were carried out with the same electrode system placed in a cell through which a weak flow of dried air was maintained the flow rate being 0.5 l/min. The electrode to create the surface discharge (corona electrode) is a multistriped one its thickness about 30 nm (Fig. 1) and it is placed on a dielectric plate of alumina. Plates with an additional thin layers of glass enamel, SiO₂ or Ba₀.₇Str₀.₃TiO₃ (BST) on the barrier surface together with the multistriped electrode were also used. The corona electrode is grounded through a measuring resistance (Rsh). The high potential from the a.c. voltage source is connected to the bottom flat electrode (Fig. 2) cooled by water. All outer edges of both electrodes are covered by an epoxy compound to prevent the surface discharge in this zone.

The third plane electrode connected to the d.c. voltage source is placed at a distance of 1 cm from the surface of the barrier.

Fig. 1. Electrode system to create surface discharge.

Fig. 2. Electrical circuit. R₁ = 20 kOhm, R₂ = 5.1 kOhm. Rsh (shunt) = 7 Ohm.
The electrical circuit to measure microdischarge and direct currents is given in Fig. 2. The joint arrangement of the surface discharge electrodes and the third plane metallic electrode (45x60 mm) is shown as well together with measuring elements and the oscilloscope. The high d.c. potential is connected to the third electrode through a microampermeter and shunting resistors to prevent the destroy microampermeter in case of a breakdown in the gap.

The ozone concentration was measured using a “Medozone” device based on the spectral analysis.

To prevent an overheating of the barrier by the surface discharge and its influence on the ozone concentration, all ozone measurements were carried out during 1 minute maximum of the discharge existence.

3. Influence of the d.c. voltage on the microdischarge currents of the surface discharge.

A typical oscillogramm of the current through the shunt $R_{sh}$ is given in Fig. 3 and shows the displacement a.c. current together with the microdischarge current pulses for a.c. voltage $U_{AC} = 2.9$ kV and $U_{DC} = 6$ kV. The negative half-cycle in the oscillogram is for a positive potential on the surface discharge electrode and positive microdischarge current pulses are seen which are much more powerful than the negative ones.

Mean values of positive microdischarge currents for at least three oscillograms were calculated for different values of a.c. and d.c. voltages and alumina barrier without and with a BST and SiO$_2$ film on the surface (Fig. 4). In Fig. 4 curve B is for the barrier surface without a film, curve C is for BST film and curve D – for SiO$_2$ film. Analogical experiments done for $U_{AC} = 2.7$ kV and all other same conditions show the same effect of the third electrode potential on the microdischarge: initial increase of the microdischarge current pulses with an increase of the positive $U_{DC}$ values and subsequent decrease for $U_{DC} \geq 5 - 6$ kV.

When a negative potential is applied to the third electrode, the effect is even more pronounced.

Fig. 3. Typical oscillogramm of the microdischarge current in a three-electrode system.

Fig. 4. Mean values of the microdischarge current pulses amplitudes as a function of the d.c. voltage. $U_{AC} = 2.9$ kV.

4. Influence of the d.c. voltage on the ozone concentration

The effect of the d.c. voltage applied to the gas gap on the ozone formation in the surface discharge depends not only on the d.c. voltage value and its polarity but on the intensity of the surface discharge itself.

As the surface discharge intensity depends on the material and the structure of the barrier surface [4] the character of the $C_{ozone} = f(U_{DC})$ dependence is different for different barriers (Fig. 5).

Curves B and C in Fig.5 are for alumina barrier with an enamel layer and $U_{AC} = 3.8$ kV. D and E correspond to alumina with a BST layer and $U_{AC} = 2.2$ kV. F and G in their turn correspond to alumina barrier without a layer and $U_{AC} = 2.1$ kV. B, D and F curves (dash lines) are for positive $U_{DC}$ of the third electrode. C, E and G curves are for negative $U_{DC}$ of the third electrode.

In a whole application of the d.c. potential to the third electrode decreases the ozone formation for $U_{DC} \geq 4$ kV. Besides, effect of the negative polarity is more pronounced.

Fig. 5. Influence of the positive or negative potential on the third electrode on the ozone concentration in the gas at the outlet of the cell.
5. Direct current formed by the third electrode

Measurements of the direct current formed in the circuit with the d.c. voltage source have shown that the intensity of the charged species formation depends essentially on at least three factors:
- the value of the a.c. voltage that forms the surface discharge (Fig. 6);
- the value of the d.c. voltage that forms the current in the d.c. voltage circuit;
- the properties of the barrier surface layer [4].

It must be noted that the direct current measured by the microamperimeter in reality (Fig. 2) constitutes of numerous impulse currents of microdischarges the duration of which is in the range of tens of ns. The inertia of the micrometer permits to measure only the constant component of the current.

6. Discussion

It has been assumed in [3] that for the conditions used in our experiments (the a.c. voltage frequency \( f = 13.7 \text{ kHz} \), the d.c. voltage up to 10 kV and the gas gap \( d = 10 \text{ mm} \)) there must be a volume charge in the gas gap formed by ions that are created in the surface discharge and move to the third electrode. A possibility of the volume charge to be present in the gap can be explained by means of a schematic oscillogram shown in Fig. 7. For \( f = 13.7 \text{ kHz} \) of the a.c. voltage the time of 1 cycle is about 70 \( \mu \text{s} \).

The microdischarges appear only during a short part of each half-cycle of the a.c. voltage (Fig. 3). For the voltage \( U_{\text{AC}} = 2.9 \text{ kV} \) this time is about 13 \( \mu \text{s} \) (Fig. 7). Let us analyze the processes for a positive potential of the third electrode. The time of the drift of negative ions through the gas gap towards the third electrode can be roughly estimated if the electric field is known.

For a first approach the field in the gap between the stripped electrode and the d.c. one can be taken as a uniform. If the d.c. voltage is equal to \( U_{\text{DC}} = 10 \text{ kV} \) and the gas gap \( \delta = 1 \text{ cm} \) then the field can be roughly estimated as \( E_{\text{DC}} = U_{\text{DC}}/\delta = 10 \text{ kV/cm} \). In this case the drift time can be found using well known values of the mobility of negative ions. In our case the time of the drift of negative ions in air through the gap is about 45 \( \mu \text{s} \). The time between the appearance of two subsequent groups of microdischarges is about 20 - 25 \( \mu \text{s} \) (see Fig. 7).

It means that the flow of negative species that drift towards the positive third electrode still exists in the gap when the new portion of microdischarges corresponding to the next half-cycle of the a.c. voltage appears. These last microdischarges appear and develop in an additional electric field of a volume charge that was formed in the gap in the previous half-cycle and still exists.

According to Fig. 6 the direct current can be up to 800 \( \mu \text{A} \). This current is formed by a flow of charged species that emerge from the whole multistripped electrode. The square of the d.c. electrode area (Fig. 1) is equal to 23 \( \text{cm}^2 \). It means that for \( I_{\text{DC}} = 800 \mu \text{A} \) the charge flow to each square cm of the electrode area can be estimated as 34.8 \( \mu \text{A/cm}^2 \). As the flow lasts about 45 \( \mu \text{s} \) and the width of the gas gap is 1 cm so it can be very roughly estimated that the net volume charge in the gas gap during the flow existence can be up to \( 1.5 \times 10^{-9} \text{ C/cm}^3 \).

The electric field of this volume charge alone is not high enough to produce ionization in the gas but it changes the conditions of all other processes connected with microdischarges. If the volume charge is diminished by, for instance, an increase of the air flow (Fig. 8) an increase of the direct current is detected.
The light emission measurements for wave length $\lambda = 337.1$ nm [3] indicate that with application of a d.c. potential to the third electrode the thickness of the plasma layer near the barrier is changed. For both d.c. potential polarities the zone filled by the light (plasma layer) moves slightly away from the barrier and is a bit wider if the positive d.c. potential is applied. The values of light emission intensity for $\lambda = 337.1$ nm and for all values of the positive d.c. voltage are less than without it, whereas the negative d.c. voltage increases the light emission. Such result can be explained by changes in the electron density in the plasma layer when the d.c. field is applied. For positive polarity of the third electrode electrons partly drift out of the layer, the number of excitation reactions with nitrogen molecules in the plasma is decreased and it decreases the light emission connected with the deexcitation. For negative polarity the processes are opposite.

The same influence of a change of the electron density in the plasma layer under the influence of the third electrode potential is detected when the ozone concentration is measured (Fig. 5). At first when the values of the d.c. voltage are not high there can be even an increase of $C_{oz}$ as it is seen for an enamel layer on the barrier surface and positive potential of the third electrode. In this case the electrons are extracted from the plasma layer into the gas gap and the probability of the reactions that lead to ozone production is increased. But with an increase of the volume charge the electric field of negative charges diminishes the electron flow from the plasma layer and it explains a decrease of ozone formation for $U_{DC} > 4 - 5$ kV (Fig. 5).

Some modeling of the electric field strength $E$ distribution in the gas gap along the distance $D$ between the strip electrode edge and the third electrode has been done. The electric fields created by the strip electrode, by the charge on the barrier surface and by the volume charge that appears in the gap when the charged species are extracted by the $U_{DC}$ from the surface discharge layer, are taken into account. The $E = f(D)$ curves for two values of the net volume charge and positive $U_{DC}$ (Fig. 9) show a decrease of $E$ values in the zone filled by the surface discharge plasma layer while in the main part of the gap the field is practically the same as defined by the d.c. potential.

7. Conclusion

By analyzing the experimental data on the influence of the additional d.c. voltage on the processes created by the surface discharge it is supposed that one of the main factors to change the intensity of the electrical and plasma-chemical processes in the gas gap is the electric field of the volume charge that appears when the charged species are extracted by the $U_{DC}$ from the surface discharge layer and a direct current exists. Electric field calculations show a possibility of such an assumption.

8. Acknowledgements

The work is supported by the RFBR (Russian Fund for Basic Researches). Grant No 15-08-04384

9. References