Numerical simulation of the surface barrier discharge in the air

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Abstract. Preliminary numerical calculations have been carried out, demonstrating the formation of a streamer structure of the surface dielectric barrier discharge in the case of the application of a positive potential to the working electrode. The dynamics of electron density and electric potential for a streamer form of discharge is presented.

1. Introduction
The dielectric barrier discharge, as is known, has two forms of development: volume and surface. In a volume discharge, the gas layer in which the discharge develops is located between the dielectric-coated electrodes. In the surface discharge, when two electrodes of different widths are separated by a dielectric, it lies directly on the surface of the dielectric. The smaller electrode, to which a voltage is applied, and at the edge of which a discharge develops, will be called a high-voltage or working electrode. The potential of the opposite will be considered zero.

An intensive study of the surface barrier discharge began only a few years ago due to its promising use for controlling the laminar-turbulent transition and the position of air flow separation zones near solid surfaces by changing the parameters of the boundary layer [1-4]. In recent years, various models and numerical experiments based on them have appeared, which allow predicting the parameters of a surface barrier discharge depending on external conditions [5-11]. It should also be noted that researchers are looking for ways to control the parameters of barrier discharges, including in the case of surface organization [12-16]. Accordingly, existing models and their numerical implementations are being developed.

In this regard, the aim of the presented work was to simulate the simplest version of the implementation of the surface barrier discharge in air at atmospheric pressure in the case of positive polarity applied voltage.

2. Model description
Air is a multi-component molecular gas characterized by a vast set of elementary processes occurring on varied spatial and time scales. This is why the choice of a plasma-chemical model depends on the formulation of the problem.

In this work, air was considered as a mixture of nitrogen and oxygen (77% N₂, 23% O₂). Here, we applied a set of plasma-chemical reactions developed in other work [17], which considered only positive and negative molecular ions O₂⁺ and O₂⁻ of air and six reactions containing these ions (table 1).
The exclusion of nitrogen in the set of ions presented for the surface barrier discharge was possible because of both the large speeds of recharge and the conversions of N$_2^+$ and N$_4^+$ ions into O$_2^+$ ions [11].

In the chain of conversion and charge-exchange reactions (N$_2^+$ + N$_2$ → N$_4^+$ + N$_2$(O$_2$), N$_4^+$+O$_2$ → 2N$_2$+O$_2^+$ and N$_4^+$+O$_2$ → N$_2$+O$_2$), N$_2^+$ and N$_4^+$ ions produce O$_2^+$ ions. At atmospheric pressure, this occurs on a time scale on the order of 1 ns, which is much shorter than less time to establish a discharge.

Table 1. Set of plasma-chemical reactions

| №  | Process                        | Reaction constant, $k_{j}$                                         |
|----|--------------------------------|-------------------------------------------------------------------|
| 1  | e+O$_2$→2e+O$_2^+$             | Convolvion of EEDF with cross section                             |
| 2  | e+2O$_2$→O$_2$+O$_2^+$         | 1.4·10$^{-29}$(300/$T_e$)·exp($-600/T_g$)·exp(700·($T_e$−$T_g$)/($T_e$·$T_g$)); cm$^6$s$^{-1}$ |
| 3  | e+O$_2$+N$_2$→N$_2$+O$_2^+$    | 1.07·10$^{-31}$(300/$T_e$)$^2$·exp($-70/T_g$)·exp(1500·($T_e$−$T_g$)/($T_e$·$T_g$)); cm$^6$s$^{-1}$ |
| 4  | e+O$_2$→O$_2$                 | 2·10$^{-2}$(300/$T_g$)$^{1/2}$; cm$^3$s$^{-1}$                   |
| 5  | O$_2$+O$_2$→e+2O$_2$          | 8.6·10$^{-10}$·exp($-6030/T_g$)·(1−exp($-1570/T_g$)); cm$^3$s$^{-1}$ |
| 6  | O$_2^+$+O$_2$→2O$_2$           | 2·10$^{-7}$(300/$T_g$)$^{1/2}$·(1+10$^{-18}$N(300/$T_g$)$^2$); cm$^3$s$^{-1}$ |

To perform a numerical simulation a fluid model of electrical discharge was formulated [15]. It is based on density balance equations for electrons, positive and negative ions, electrons heat balance equation, which takes into account not only the volume processes, but also the spatial transfer by conduction and the Poisson equation for finding a self-consistent electric potential. The mobility and diffusion coefficients for electrons, as well as some constants of the inelastic processes involving them, are calculated by convolving the electron distribution function $f(w,T_e)$, with the cross section $\sigma(w)$. In this work the electron distribution function $f(w,T_e)$ is assumed Maxwellian.

Figure 1. Schematic configuration of the electrodes in the discharge

3. Numerical simulation and results
Simulation was performed for a positive potential of the working electrode V = 3.5kV, which has the shape of a step. The rising front lasts for t = 1ns. The thickness of the dielectric was set equal to d = 55 μm, and its dielectric constant was $\varepsilon = 5$. 
Figure 2. Distribution of electron density (left) and potential (right) at different points in time.
As can be seen from the obtained results, a streamer is generated near the edge of the loaded electrode and propagates along the surface of the dielectric at some distance from it. The propagation process takes about 110-150 ns, then occupying the entire region begins to fade out slightly.

4. Conclusions
Thus, as a result of the work, a model describing the surface dielectric discharge in air was formulated. Preliminary numerical calculations have been carried out, demonstrating the formation of a streamer structure of the discharge in the case of the application of a positive potential to the working electrode. The dynamics of electron density and electric potential for a streamer form of discharge is presented.

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