DISTRIBUTION OF ELECTRIC FIELD BETWEEN ELECTRODES IN PLASMA JET: COMPUTATIONAL STUDY

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Abstract: *Gliding Arc discharges are recently used in many environmental, biomedical and industrial applications. The discharge is generated between two diverging electrodes at atmospheric pressure. In this paper we present the computational study of the influence of*
I. the geometry shape of electrodes,
II. distance of the gap between electrodes and
III. the bias on the powered electrode
on electric field distribution between the electrodes. We focused our attention especially on the influence of these parameters on the breakdown voltage needed for the discharge ignition. The mathematical model is based on standard equations of electrostatics, the numerical realization and data processing was performed in the program COMSOL Multiphysics. It was found that the geometry shape of electrodes significantly influences the value of the breakdown voltage.

Key words: *Gliding arc discharge, electric field distribution, atmospheric pressure, geometry shape of electrodes, computational study, COMSOL Multiphysics.*

1. Introduction

Plasma discharges in gases exist in a large variety of forms, which differ significantly in many aspects. For utilization of plasma in technical applications it is usually appropriate to use discharges characterized by the high electron density, high electron temperature and high ability to transmit the energy from power supply into plasma. These properties increase the number of chemical reactions undertaken by the particles in the volume, which leads to the decreasing of the processing time and higher efficiency of the device.

In several past decades microwave discharges at low pressure were intensively studied, because this kind of plasma meets sufficiently the above mentioned criteria. In environmental applications it is usually impossible to use this well established technology, because the large volume of treated material usually requires to work at atmospheric pressure and in continual regime. In these situations Gliding Arc discharges seems to be suitable alternative providing similar advantages as the microwave plasma, moreover with lower costs for the acquisition of the equipment. Gliding Arc discharges are being recently utilized for decontamination of water and air [1-5], degradation of various compounds [5-10] modification of surface properties of solid materials [11-13] or production of hydrogen [14-15]. The large number of applications of gliding arc is possible due to the non-equilibrium character of this kind of plasma discharge, which consequently enables to produce relatively high number of charged and highly reactive particles.

Gliding Arc discharge is usually generated between two diverging electrodes, which are placed in a gas flow. The breakdown starts in the place with highest intensity of electric field, i.e. in the area with shortest distance between electrodes. The ignition of the discharge occurs, when the breakdown field intensity in air is reached (about 3.000 V.mm^{-1}). Consequently, the flowing gas blew the developed discharge channel, whereas the discharge transmits from the equilibrium stage to the non-equilibrium one. The plasma channel perishes at the moment, when the energy losses from the channel overcome the amount of supplied energy. Flowing air cools down the electrodes heated by plasma discharge and it also reduces the temperature of the gas. It allows to use this type of plasma discharge for treatment of biologically active material [16-17].

The theme of this paper is motivated by some problems with the ignition of the arc in our experiments. The distribution of electric field intensity in the vicinity of electrodes is mainly influenced by

I. the geometry shapes of electrodes,
II. the size of the gap between electrodes and
III. the electric bias on the powered electrode.

We studied computationally the influence of these parameters on the distribution of electric field in plasma jet at the moment shortly before the electric channel formation and discharge ignition.

2. Model description

The fluid computer model is based on the numerical solution of the equations describing electrostatic field:

$$\nabla \cdot \left(\varepsilon_0 \varepsilon_\mathrm{r} \vec{E}\right) = \rho_\mathrm{V} \qquad (1)$$

$$\vec{E} = -\nabla \varphi, \qquad (2)$$

The variables are electric field intensity $\vec{E}$ and potential of electric field φ. The constant $\varepsilon_0 = 8.854 \times 10^{-12}\ \mathrm{F.m^{-1}}$ denotes permittivity of vacuum, $\varepsilon_\mathrm{r} = 1.00059$ means the relative permittivity of air and ρ_V is the volume charge density. The first equation is the differential form of Gauss's law.

The boundary equations were set to meet the following criteria:

$\varphi = 0\ \mathrm{V}$ - surface of the grounded electrode,
$\varphi = \varphi_\mathrm{L}$ - surface of the powered (right) electrode,
$\vec{n} \cdot \vec{D} = 0$ - zero charge at boundaries, which do not represent a solid surface.

The distribution of electric field intensity in the plasma jet was studied for three geometry shapes of electrodes. The first one (type A) is represented by a rectangle with rounded corner, the second one (type B) is given as a quarter of ellipse and the third one is represented by a half of circle (type C). (see scheme in the Figures 1-3).

The model was solved numerically by Finite Element Method (FEM) in the program COMSOL Multiphysics as a steady-state simulation. This program enables us to use adaptive mesh refinement in order to improve the precision of the calculation in areas characterized by sharp changes of the electric intensity. At the beginning a mesh is generated in the working area, which is being consequently refined during the calculation. Due to this, the precision of results increases, whereas both the calculation time and the hardware requirements decrease. Examples of the working area with various types of initial meshes are shown in the Figure 4.

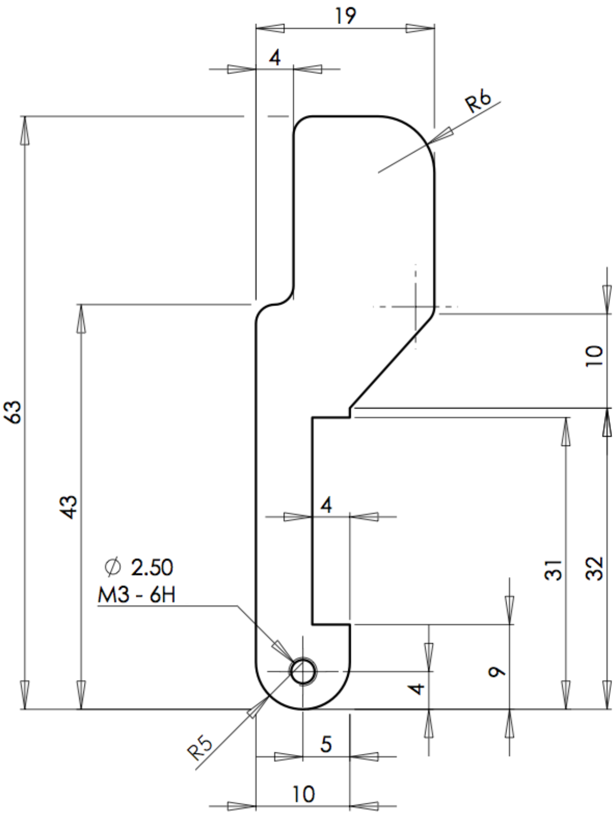


Fig. 1. Geometry shape of the electrode (Type A).

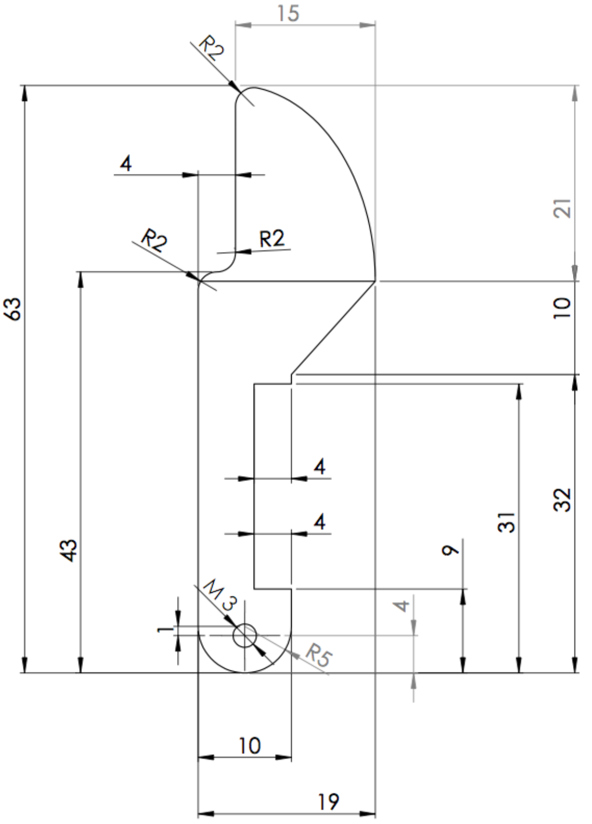


Fig. 2. Geometry shape of the electrode (Type B).

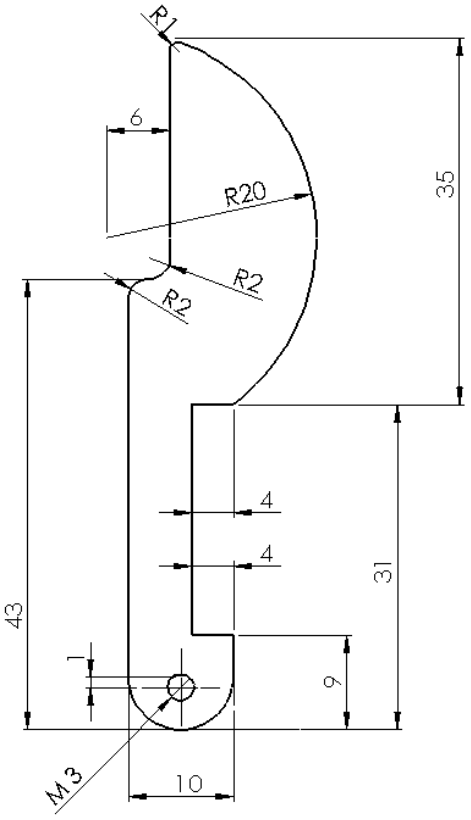


Fig. 3. Geometry shape of the electrode (Type C).

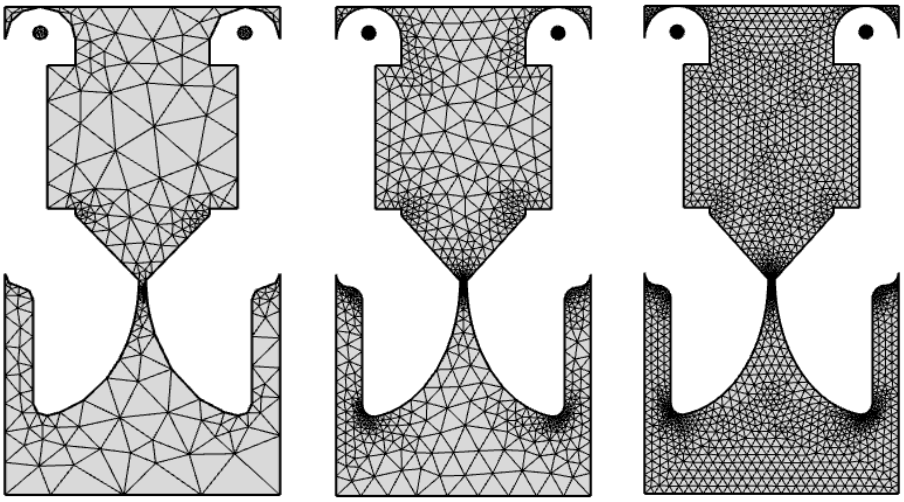


Fig. 4. Various types of meshes: extra coarse, normal and extra fine.

3. Results and discussion

For each geometry shape a series of calculations was performed, whereas the distance between electrodes was the main variable parameter. This distance varied from 1 to 5 millimeters with the spatial step 1 mm. The goal of the calculation was to estimate such a bias at the powered electrode, which will corresponds to the situation, when the conduction channel is formed and the discharge is being ignited.

In order to estimate this value, the bias on the powered electrode increased from the initial value with the step +100 V, till the electric field intensity somewhere between electrodes reached the value about 3.000 V.mm^{-1}, which is the breakdown electric intensity in air.

The Figure 5 summarizes data obtained by the calculation and it clearly demonstrates the significant dependence of the breakdown voltage on the geometry shape of electrodes. The usage of the elliptical electrodes (*Type B)* enables to ignite the plasma discharge at the voltages about 22 percent lower in comparison with the *Type A* or *Type C* electrodes and at the same distance between them. As shown in Figure 5 the breakdown voltage increases linearly with the distance of electrodes.

Distribution of electric field intensity shortly before the discharge channel formation for various distances of electrodes is presented in the Figures 6-8. Equipotential curves of the electric field between the electrodes show huge gradient of intensity of electric field. The difference between intensity of electric field between electrodes and other areas are massive.

The above presented calculations were performed with respect to the assumption, that the voltage required for the discharge ignition is independent on the velocity of the flowing air. Naturally, primary electrons are presented in the gas and in the initial phase they are playing a key role in the process of channel formation. These electrons are drifted together with the flowing gas away from the nozzle, so at higher velocities they could not gain enough energy in order to form the discharge channel.

Friedman et al. [18] derived the characteristic time τ_i of the arc formation from the kinetic equation for electrons

$$\frac{\partial n_\mathrm{e}}{\partial t} = k_\mathrm{i} n_\mathrm{e} n_0 \approx \frac{n_\mathrm{e}}{\tau_\mathrm{i}}. \qquad (3)$$

In Equation 3 k_i denotes the ionization coefficient, t is time and n_e and n_0 are the electrons and gas concentrations. In the case of clear air the value of characteristic time is about $1\,\mu\mathrm{s}$ [19]. Ordinary plasma jets operate with the gas velocity in order of several of tens meters per second. For these parameters, the displacement of conducting channel from the initial position because of the gas flow is only about 1×10^{-5} m, so it does not significantly affect the channel formation.

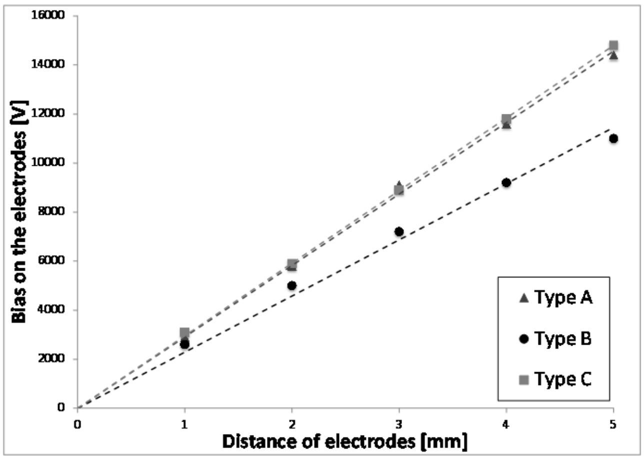


Fig. 5: Dependence of the bias on the distance of electrodes at the moment of discharge ignition for studied geometries.

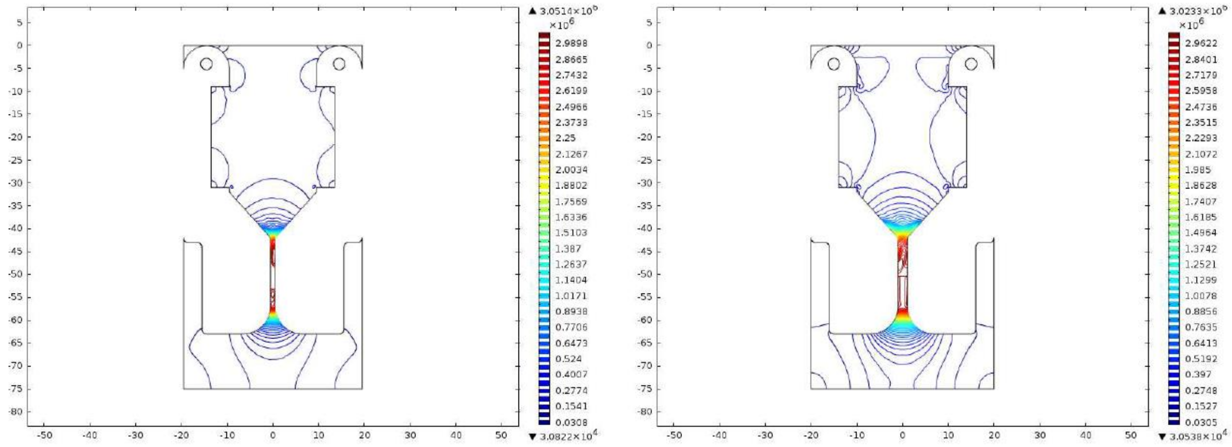
Finally, two remarks should be stated:

a) The distribution of the electric field intensity was calculated for the predetermined value of breakdown electric intensity. The precise moment of the discharge ignition and the precise breakdown voltage is not given by this value only, but it depends also on other parameters, for example, whether an AC or a DC voltage is used.

b) Although the influence of the geometry shape of electrodes on the distribution of the electric field intensity was discussed in the paper, one should have in mind that the choice of the best electrode profile should be done also with respect to the discharge lifetime. Different shapes of the electrodes with spikes and sharp edges can make for lower values of the breakdown voltage, but their lifetime is very short because of the high temperature on the pikes so they can be damaged quickly by heat. This is important for the most of environmental applications.

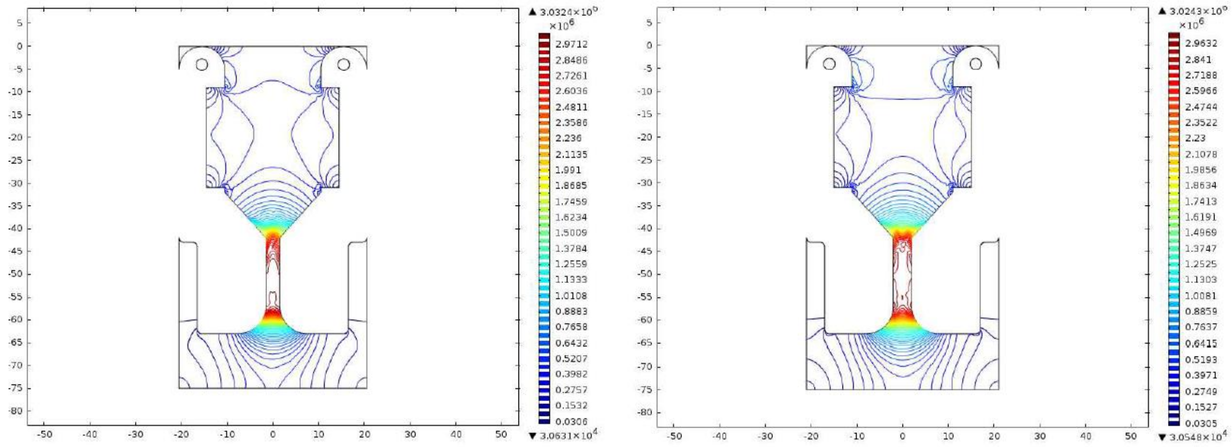
d = 1 mm, U = 2.900 V

d = 2 mm, U = 5.800 V



d = 3 mm, U = 9.100 V

d = 4 mm, U = 11.600 V



d = 5 mm, U = 14.400 V

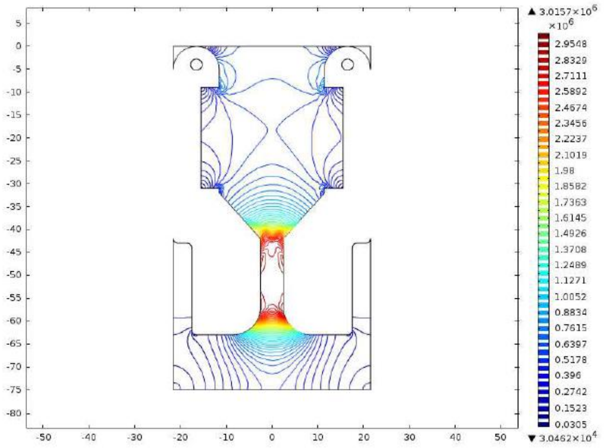
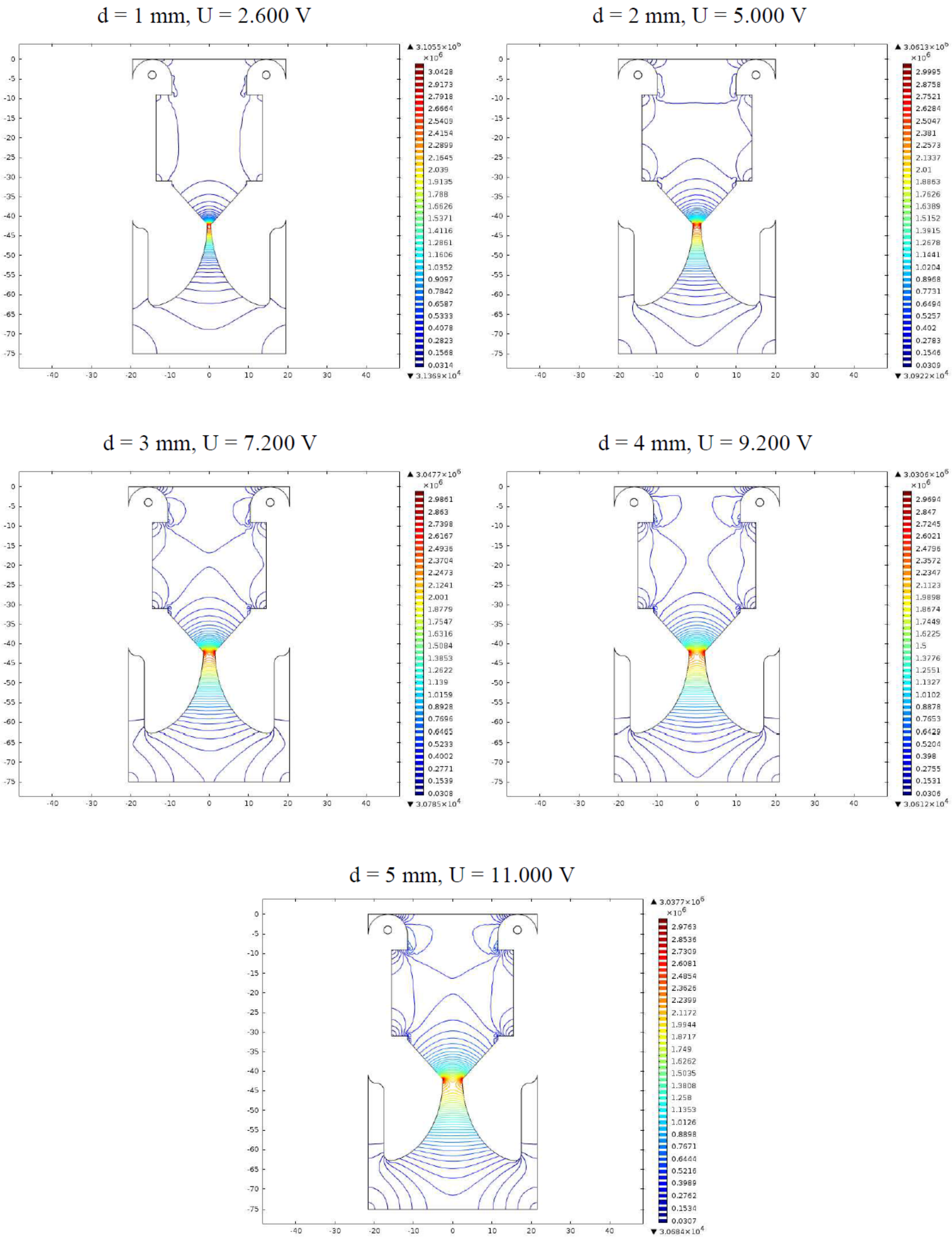


Fig. 6: Distribution of electric field intensity in dependence on the distance of electrodes (type A).



d = 1 mm, U = 2.600 V

d = 2 mm, U = 5.000 V

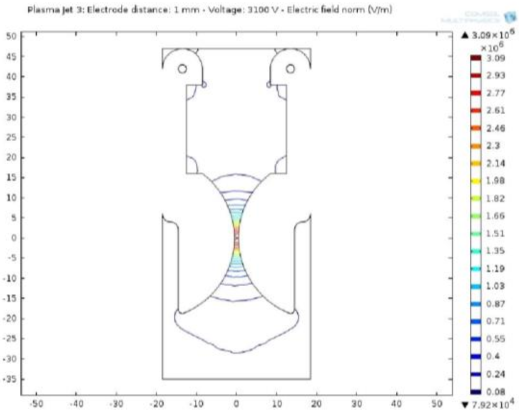
d = 3 mm, U = 7.200 V

d = 4 mm, U = 9.200 V

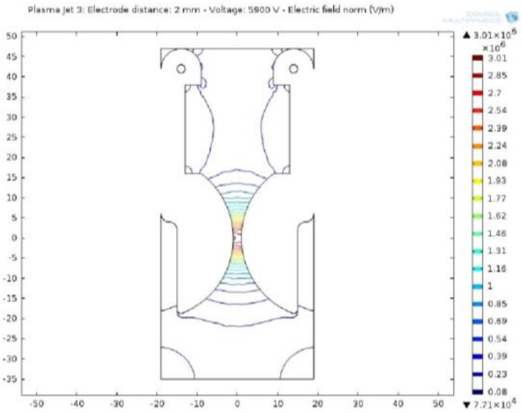
d = 5 mm, U = 11.000 V

Fig. 7: Distribution of electric field intensity in dependence on the distance of electrodes (type B).

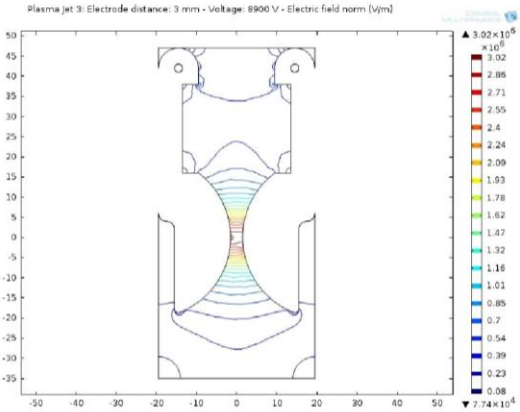
d = 1 mm, U = 3.100 V



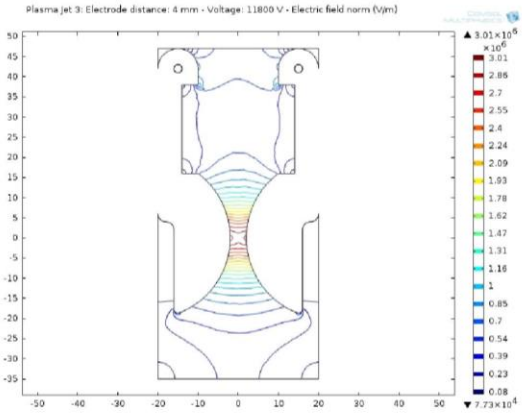
d = 2 mm, U = 5.900 V



d = 3 mm, U = 8.900 V



d = 4 mm, U = 11.800 V



d = 5 mm, U = 14.800 V

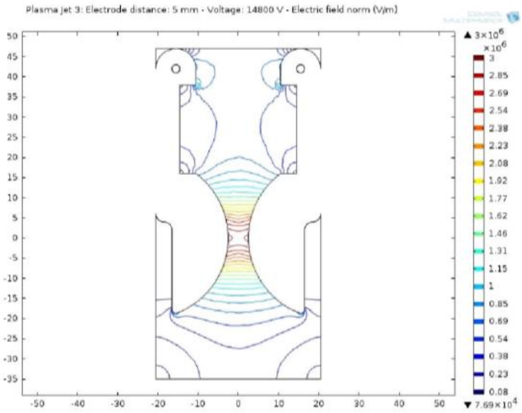


Fig. 8: Distribution of electric field intensity in dependence on the distance of electrodes (type C).

4. Conclusion

It can be concluded that the electrode geometry shape significantly influences the distribution of the electric field between electrodes of the plasma jet. In the studied case, the breakdown surface potential reached the value about 22 percent lower in the case of the elliptic-shaped electrodes (*Type B*) in comparison with the rectangle-shaped ones (*Type A*) or half of the circle-shaped (*Type C*).

The surface bias, which is necessary for the gliding arc discharge ignition, increases linearly with the distance of electrodes.

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