High-voltage electrode optimization towards uniform surface treatment by a pulsed volume discharge

A V Ponomarev[1,4], M S Pedos[1], S V Scherbinin[2], Y I Mamontov[2] and S V Ponomarev[3]

[1] Institute of Electrophysics, 106 Amundsena Street, Ekaterinburg, 620016, Russia
[2] Ural Federal University, 19 Mira Street, Ekaterinburg, 620002, Russia
[3] Tomsk Polytechnic University, 30 Lenina Street, Tomsk, 634034, Russia
[4] Author to whom any correspondence should be addressed

E-Mail: apon@iep.uran.ru

Abstract. In this study, the shape and material of the high-voltage electrode of an atmospheric pressure plasma generation system were optimised. The research was performed with the goal of achieving maximum uniformity of plasma treatment of the surface of the low-voltage electrode with a diameter of 100 mm. In order to generate low-temperature plasma with the volume of roughly 1 cubic decimetre, a pulsed volume discharge was used initiated with a corona discharge. The uniformity of the plasma in the region of the low-voltage electrode was assessed using a system for measuring the distribution of discharge current density. The system's low-voltage electrode – collector – was a disc of 100 mm in diameter, the conducting surface of which was divided into 64 radially located segments of equal surface area. The current at each segment was registered by a high-speed measuring system controlled by an ARM™-based 32-bit microcontroller. To facilitate the interpretation of results obtained, a computer program was developed to visualise the results. The program provides a 3D image of the current density distribution on the surface of the low-voltage electrode. Based on the results obtained an optimum shape for a high-voltage electrode was determined. Uniformity of the distribution of discharge current density in relation to distance between electrodes was studied. It was proven that the level of non-uniformity of current density distribution depends on the size of the gap between electrodes. Experiments indicated that it is advantageous to use graphite felt VGN-6 (Russian abbreviation) as the material of the high-voltage electrode's emitting surface.

1. Introduction

A pulsed volume discharge is of great interest for the creation of significant volumes of low-temperature plasma within gaps up to tens of centimeters [1]. Processes in the pulsed volume discharges are similar to processes in the classical stationary glow discharge, where cathode and anode fall off potentials, Faraday dark space and positive column exist. At the same time, the volume discharge possesses some significant differences from the classical glow discharge. One of them is that to materialize such a discharge a pre-ionization of gas is needed, which can be performed with auxiliary discharges such as DBD, corona, spark. Another difference is that this type of discharge is not stationary. If its duration won't be limited artificially, it will certainly constrict into a single conducting channel. Also, one more difference is its specific peak power which can exceed 1 MW/cm^3, that significantly exceeds the similar characteristics of a classical glow discharge. Unlike the classical low-pressure discharge, the pulsed high-pressure discharge was given the name transient glow discharge [2] but it most often referred to as pulsed glow discharge. It may be that this discharge would be more properly referred to as a high-pressure glow discharge, but the term 'volume discharge' had come into wide use before their kinship was established. The adjective 'volume' emphasizes the fact that the characteristics of this discharge are determined primarily by the process in the discharge itself and not related to its interaction with the chamber walls, as is the case with classical glow discharge. Volume discharge has wide practical use. These discharges are used for laser pumping for various technological applications. Furthermore, it is used to construct plasma-chemical reactors and also to initiate and support various processes on the surface of solid bodies [3].

Regardless of the majority of work in the field of pulsed volume discharge being done in late last century, the interest towards this type of discharge remains high even today. Research continues to study its characteristics [4], and systems are constructed on its basis. Reference [5] proposes a system based on pulsed volume discharge for decontamination of surfaces.

Pulsed volume discharge has a diffuse nature and enables to treat larger surfaces per pulse when compared to other discharge types. But effective treatment requires a uniform distribution of discharge current density on the entire surface of the object being treated. Research of current density distribution in pulsed volume discharge is presented in this paper. Factors affecting current distribution on the surface of the low-voltage electrode are discussed. The shape and material for the emitting surface of the high-voltage electrode in a gas discharge system are presented.

2. Experimental setup and methods

The set of equipment used for studying the pulsed volume discharge parameters consisted of a high-voltage generator DOPG-0.7 [6] and a system to measure the uniformity of current density distribution in sections [7].

The generator is a modular structure consisting of 2 separate parts: power and high-voltage modules. The high-voltage module contains a high-frequency transformer, whose windings ratio defines the output voltage and inductivity of windings - the rate of high-frequency oscillations. The output transformer allows easy alignment the output impedance of the generator with the impedance of various loads in a wide range for effective energy transfer into them. To change the parameters of a discharge or its configurations it is enough to change either the high-voltage module itself or the transformer located in it. The power module remains unchanged in all configurations.

The generator is capable of forming pulses of damped harmonic oscillations with a frequency up to 1 kHz. Herewith, the rate of high-frequency oscillations themselves can reach units of megahertz. The maximum energy of the output pulse at optimal resistive load at frequency of 1 MHz reached 0.4 J. The advantage of this generator type is that for one power pulse it is capable of repeatedly generating a plasma in the discharge gap. This results in the increase of the plasma interaction time with the treated object, with the preservation of all advantages of pulsed operation mode. In addition, it increases the actual repetition rate of discharge pulses that will be equal to the multiplication of generator operation rate by the number of plasma generation moments per one pulse.

The discharge in the configuration "multi-needle high-voltage electrode – grounded plate" was ignited within gaps from 55 to 125 mm. Changing the gap between electrodes changed the strength of the electric field in the gap. This was the only possible way to change the strength of the electric field in our case. The generator's output parameters are constant and depend on the high-voltage transformer's parameters only.

A high-speed multi-channel measurement system of the current density distribution of a completed pulsed corona discharge has been used based on a 32-bit ARM™ microcontroller.

A photograph of a single pulsed volume discharge in air at atmospheric pressure and outside view of the measuring system are provided as figures 1(a) and 1(b), respectively.

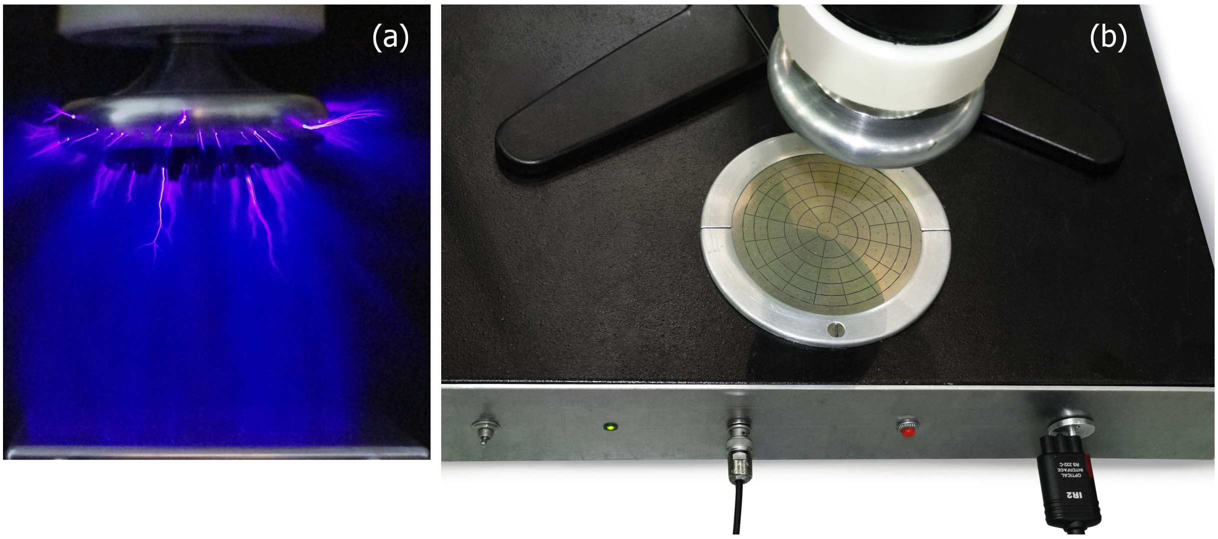

Figure 1. A photograph of a single pulsed volume discharge in air at atmospheric pressure (a); outside view of the measuring system (b).

The system allows the current density distribution on a grounded electrode – collector to be determined for both a negative and positive current. The collector consisted of a nickel-plated double-sided PCB-plate of 100 mm in diameter, the outer track of which was divided by gaps of 0.5 mm width into 64 radially located segments of equal surface area. Discharge current passing through the circuits of each segment induced a charge in the measuring capacitor. The voltages of 64 measuring capacitors were directly proportional to the induced charges and were measured by an automated system. Discharge current of only one polarity could be measured in one experiment.

The device provides the ability to measure the current density distribution as a single pulse and to operate in the accumulation mode of measurement results. The sampling time per measurement channel does not exceed 1 µs, which allows for a pulse repetition frequency of a current in units of kilohertz with 64 channels used in the work.

The results of the measurements are transmitted to a personal computer, where they are processed and rendered. To facilitate the interpretation of results obtained, a computer program was developed to visualise the results. The program provides a 3D image of the current density distribution on the surface of the low-voltage electrode. The images provided as column graphs were used as a basis when assessing the uniformity of the distribution of discharge current.

A TDS 684B oscilloscope with a 1 GHz bandwidth and Barth Electronics wide band signal attenuators were used for recording the current pulses.

3. Experimental results

3.1. Shape and material of the high-voltage electrode

As indicated above, gas ionisation is a necessary preparation for the ignition of a pulsed volume discharge. In our case, a corona discharge was used as an auxiliary discharge. Our choice was based on the fact that a high-strength electric field in the gap is needed for the ignition of both the auxiliary and the main discharge. The source of high-voltage used, i.e. the generator DOPG-0.7 enables to achieve an electric field with the strength of roughly 1 MV/m in the first half-period of the oscillation, if the discharge gap is 0.1 m.

One of the traditional methods of facilitating the ignition of a corona discharge is to use sharp-pointed electrodes that increase the electric field's strength due to their heterogeneous geometry. To form a discharge with a larger surface or a longer duration, multi-needle electrodes are used. In previous studies [8], the authors used a multi-needle electrode made of copper wire. The emitting surface of such a high-voltage electrode had a diameter of 60 mm and consisted of ~8,000 wires of 0.13 mm in diameter and roughly 20 mm in length. The main disadvantage of this design is its inconvenience of technological manufacture. Other disadvantages are the impossibility of precise formation of the emission surface shape as well as the difficulty of keeping its shape unchanged during its subsequent use.

A more advantageous material for the emitting surface of the high-voltage electrode was found to be graphite felt VGN-6 (Russian abbreviation). It is a flexible sheet inorganic conductive material. Felt consists of individual thin hairs, which provide significant number of micropoints on the surface. Micropoints in its turn made the corona discharge ignition easier.

In the course of research it was found that the material possesses a very convenient property of self-formation of its surface. When working with a freshly made electrode at the discharge currencies of about one ampere, individual hairs excessively projecting out of the electrode’s surface were gradually burned out. Being made of carbon, the hairs burned off in air and the electrode’s surface become uniform with only a short training.

The system’s operation was affected not only by the shape and material of the high-voltage electrode’s emitting surface. High-strength electric field for efficient ignition of a pulsed volume discharge cannot be achieved without careful design of the high-voltage electrode as a whole. It is determined that the most efficient form of the electrode is an axially symmetrical rotational body. Other forms, including sharp edges, brought along non-uniform distortions in the electric field and the formation of intensive streamers in those regions of the surface. This led to reduced impedance of the system and, in turn, to decreased output voltage of the generator and a decreased strength of the electric field in the gap. A drawing of an optimum shape of the high-voltage electrode to treat the surface of roughly 1 dm^2 is provided as figure 2(a). The entire electrode except the emitting surface is made of aluminium alloy. A photograph of the shape as viewed from the side of the emitting surface is provided as figure 2(b). This is the electrode that was used in all experiments described in this paper.

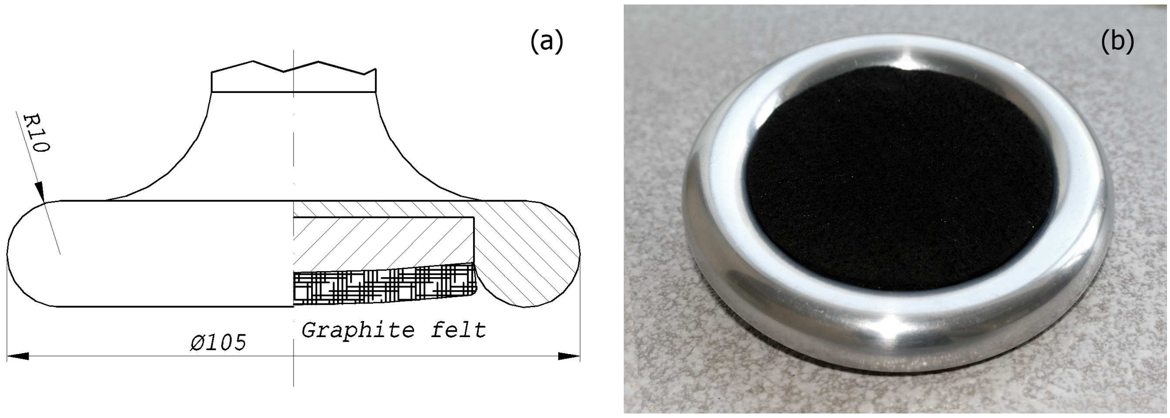

Figure 2. Design of the high-voltage electrode (a) and its outside view from the side of the emitting surface (b).

3.2. Research of discharge current density distribution on the surface of the low-voltage electrode

We assume that the objects to be treated by pulsed volume discharge will be acting as the discharge system’s low-voltage electrode. Therefore, the uniformity of the discharge current distribution on the surface of the low-voltage electrode is the most important parameter determining the effectiveness of our system functioning as a whole.

With the help of the system described above we obtained data about the uniformity of the discharge current distribution at various gap widths between the electrodes. In those experiments, we also measured the form of the current on the low-voltage electrode – the collector. Measurements were taken both in single pulse mode and in repetitive mode with accumulation of 100 discharge pulses results. In single pulse mode, the system performed 10 preparatory pulses and measured the parameters of the 11th discharge pulse. This was done to ensure identical measurement conditions in both single pulse and repetition modes. The data presented were measured at the pulse frequency of 100 Hz.

Figure 3 shows four groups of data obtained with the discharge gaps of 55, 75, 95 and 115 mm. For each group, two 3D-distributions of the induced current are presented: from a single discharge pulse and normalised across 100 discharge pulses. Axes X and Y represent the collector's dimensions in mm. The readings on axis Z are presented in arbitrary units proportional to the charge induced by the flow of discharge current in the circuit of each segment. The segments in the figure correspond to the size and shape of the actual measuring segments. For each group an oscillogram of the collector's single pulse current is provided, measured for the respective group of distances between the electrodes.

4. Discussion and conclusion

The main purpose of the research was to optimise the shape and material of the high-voltage electrode of a gas discharge system. The assessment criterion used was the uniformity of discharge current density distribution on the surface of the low-voltage electrode – the collector. It is clear that the measuring system enabled only coarse measurements of that uniformity due to the finite number of measuring segments and their significant size. For a more detailed determination of the level of uniformity of discharge current, the size of the measuring segments must be reduced and their number increased. Still, we assume that the system used by us can be successfully utilised for a qualitative assessment of the level of uniformity of discharge current. The following conclusions were made in the course of using that measuring system:

- In single pulse mode, treatment with pulsed volume discharge can be performed only at small gaps between the electrodes. But even at the minimum gap, there are observable regions on the surface of the low-voltage electrode where no current runs. With the gap widening, the number of such segments increases.
- If assessing the effects of 100 discharge pulses, current was registered in all measuring segments of the collector at small gaps between the electrodes. This may be due to shifting of emission centres along the electrode's surface. This allows for a conclusion that in repetitive mode, the entire surface of the low-voltage electrode will be treated by discharge.
- Combining the data of the distribution of currents on the surface of the low-voltage electrode and the data of the current oscillograms leads to a conclusion that the surface area of the discharge's impact on the electrode and the amplitude of the discharge current are in direct correlation to each other. From this point of view, the situation can be compared to classic glow discharge where an increase of the current leads to an increase of the area of emitting surface.
- High stability of the summary charge induced by the discharge current across pulses could be observed. The data of 10 experiments at the electrode gap of 55 mm were reviewed. For example, the mean value of all summary charges from a single pulse was 65.306 arbitrary units. The minimum and the maximum values were 62.924 and 68.017, respectively. Standard deviation of the charge value was 1.545.
- The shape of the high-voltage electrode has a significant impact on the distribution of discharge current density.

A discussion of the shape and behaviour of plotted curves of the current on the collector is beyond the scope of this paper. It must be noted that the non-symmetrical nature of the current upon symmetrical alternating voltage applied to the discharge gap is the result of non-symmetrical configuration of electrodes used. With a symmetrical configuration of electrodes, the current on the collector is also symmetrical.

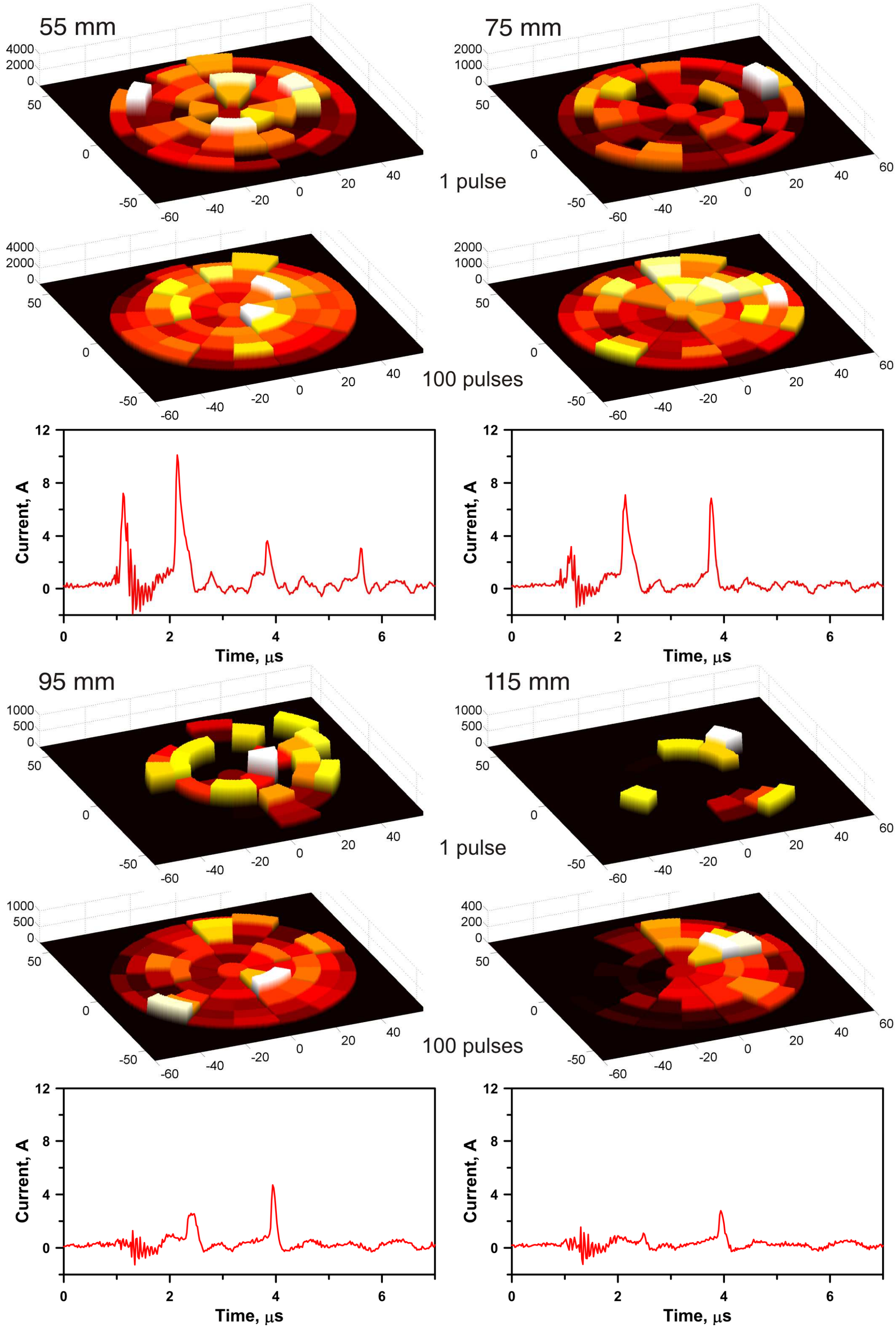

Figure 3. 3D-images of current density distribution on the surface of the low-voltage electrode, and oscillograms of currents in the collector for electrode gaps of 55, 75, 95 and 115 mm.

5. Acknowledgments

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References

[1] Korolev Yu D and Mesjac G A 1998 *Physics of Pulsed Breakdown in Gases* (Yekatriburg: URO-PRESS)

[2] Chalmers I D 1971 The transient glow discharge in nitrogen and dry air *J. Appl. Phys.* **4** 1147

[3] Osipov V V 2000 Self-sustained volume discharge *J. Phys.-Uspekhi* **43** 221-41

[4] Elistratov E A, Kuznetzov A P, Maslennikov S P, Protasov A A and Shkol'nikov E Ya 2012 Measuring parameters of volume nanosecond pulsed discharge in air at atmospheric pressure *J. Technical Phys. Lett.* **38** 793

[5] Zhuravlev M V, Slobodyan M S and Shubin B G 2012 System for atmosphere HF volume discharge *J. Izvestiya Vischih Uchebnih Zavedeniy: Phizika* **55** 456

[6] Ponomarev A V, Pudikov A S, Gusev A I and Pedos M S 2014 A solid-state generator with pulsed excitation of the oscillating circuit *J. Instrum. Exp. Tech.+* **57** 135

[7] Ponomarev A V, Pedos M S, Mamontov Y I, Gusev A I and Scherbinin S V 2015 System for measuring the current density distribution of a completed pulsed corona discharge *J. Instrum. Exp. Tech.+* in print

[8] Ponomarev A V, Pudikov A S and Ignatenko Y G 2014 Damping oscillation pulse generator for atmospheric-pressure gas discharge applications *J. Izvestiya Vischih Uchebnih Zavedeniy: Phizika* **57** 28-31