International Journal on "Technical and Physical Problems of Engineering" (IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

September 2020 | Issue 44 | Volume 12 | Number 3 | Pages 45-51

# INFLUENCE OF PARAMETERS OF DIELECTRIC BODIES AND NOZZLES ON EXCITATION PROCESS AND CHARACTERISTICS OF HIGH VOLTAGE NANOSECOND DISCHARGE IN DENSE AIR

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**Abstract-** The last decades in many world research centers carried out full-scale work on energy efficiency and energy saving. There is a gradual transition from traditional research high-voltage AC and DC voltage installations to the development of pulse installations operating in a short-term pulsed mode. This article is the next step in exploration of nanosecond discharge processes in dense air gaps and development of pulsed installations and their components (reactors) for energy-efficient cleaning of harmful gas emissions from industrial enterprises. We investigate the excitation modes of nanosecond crown discharge in dense air in presence of various dielectric barriers and nozzles on potential electrode in order to optimize the most effective discharge parameters and insulating structure of high-voltage devices. The work identified the modes to reduce the discharge delay time, formation of nanosecond volume discharge, determine the optimal distance between potential electrodes and insulating structure that does not affect the main discharge parameters (current, electric field strength, structure, etc.). The specific data on development of energy efficient electrical technologies for purification of harmful gas emissions from industrial plants are given.

**Keywords:** Nanosecond Crown Discharge, High Voltage, Delay Time, Interelectrode Distance, Gas Emissions, Reactor, Potential Electrode, Dielectric Barrier and Nozzle, Explosive Processes, Streamer Channel, Streamer's Head, "Pin" Electrode, Electric Field Strength, Excitation.

## 1. INTRODUCTION

Presented article is devoted to exploration of characteristics of nanosecond pulsed discharge in dense air gaps (on atmospheric pressure and above) under influence of high pulsed voltage. Such researches are necessary to study the breakdown processes in dense air, near-electrode areas, as well as the effect of various dielectric structures that are present in any high-voltage devices on discharge parameters. In real electrical installations, insulation gaps with dielectric elements are very common. Therefore, it is also important to know discharge development in presence of dielectrics. If there are solid dielectric inserts in discharge gap, discharge properties change. This applies to various characteristics of discharge, such as initial voltage, delay time of discharge ignition, amplitude and duration of pulse, breakdown voltage, and others.

In addition, there are works in which discharge is considered at constant voltage and ignition of discharge by nanosecond pulse with small amplitude [1, 2] and by laser [3]. Such investigations are carried out in many scientific schools in this area in order to create the most optimal designs of pulsed discharge reactors for various applications. In our case, we set the goal of studying the excitation processes of nanosecond pulsed discharge at different air pressures in the interelectrode gap, the effect of different dielectric nozzles on potential electrode on discharge formation process, on its individual parameters (discharge delay time, size of streamer zone), as well as structure discharge (branching processes of streamer channels, head sizes of streamers, etc.).

Studies of the characteristics of a short-duration pulsed discharge in various mediums have been conducted by many scientific centers for quite a long time [4, 5]. Purpose of such researches is related to their application in various technological processes. For example, pulse discharges of microsecond duration are used in aqueous mediums to create electro-hydraulic shocks applied to the cleaning of many complex structures, crushing of alloys, cleaning from corrosion, etc. Microsecond pulse discharges are successfully used to disinfect aquatic mediums from pathogenic microorganisms. Many researchers are investigating breakdown stages in gas, liquid and solid insulation when exposed to micro and nanosecond pulses. At the same time, in these mediums, high-speed processes involving high-energy electrons of anomalous energy, which does not occur in ordinary classical discharges.

Appearance of such particles leads to generation of high-frequency radiation both in near-electrode areas and interelectrode distance. As mentioned earlier, this article will consider such processes both to reduce discharge delay times and excite ionization processes far from primary ionization centers, and to optimize formation modes of maximum number of streamer channels with subsequent generation of chemically active discharge products.

These researches will help us in development of highly efficient nanosecond crown reactors to neutralize toxic gas emissions from hazardous industrial production (metallurgical, chemical, etc.).

## 2. EXPERIMENTAL TECHNIQUE PART

So, research the characteristics of nanosecond pulsed discharge in dense air, pulse generator with output voltage 80 kV was elaborated. It was assembled on basis of pulsed capacitors with charging voltage of 10 kV. "Pin-plane" electrode system with various dielectric nozzles (porcelain, fluoroplastic and plexiglass) was used in our experiments.

In this case, electrical capacitance of each parallel-connected capacitor is equal to 1000 pcF (10 steps), which, when discharged in series, makes up impact capacitance - 1000/10 = 100 pcF. Front of generated pulse is varied in range of tens nanoseconds, and duration - hundreds nanoseconds. At the same time, pulse repetition frequency is reached over 1000 Hz. With such intensity of nanosecond pulse repetition, we explore both near-electrode processes, including microexplosions on the surface of potential electrodes, the generation of high-energy electrons and accompanying X-rays, and processes in the interelectrode gap (branching of streamers, discharge structure, etc.).

Figure 1 shows the "pin-plane" electrode system of reactor of the crown discharge. In some experiments, metal ball is used instead of "pin" electrode. As can be seen from the figure porcelain and fluoroplastic nozzles were constructed on potential electrode. In some experiments, depending on design of electrode, plexiglass nozzle is used. In the case of "pin" electrode, combination of porcelain and fluoroplastic nozzles is used, and in ball one - only plexiglas nozzle. Purpose of experiments is to explore near-electrode explosive processes when nanosecond crown discharge is excited and determine dependence of discharge delay time on diameter (radius of curvature) and design of potential electrode. In experiments, position of nozzles is varied relative to the end of "pin" (ball) electrode and each other in range 1÷5 mm. By this method, we were able to determine optimal and stable excitation mode of volume nanosecond crown discharge, i.e. contributed to management of ionization processes in near-electrode areas and movement of charged particles stream in interelectrode gap. At the same time, by varying the air pressure in working chamber, we explored ionization processes both in near-electrode areas and volume gap.

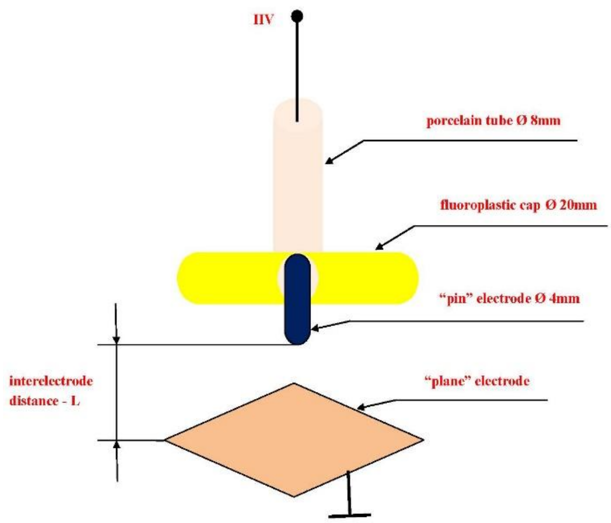



Figure 1. Design of "pin-plane" electrode system for excitation of nanosecond crown electric discharge

It was revealed how change in pressure affects change in discharge zone in transverse direction and generation of high-frequency X-ray, which is in turn consequence of formation of the high-energy electrons beams and explosive processes at potential electrode. Using stereoscopic polarizing microscope, the state of working surface of potential electrodes and dependence of explosion centers parameters on electrode's design and air pressure were investigated.

To explore of the generated X-ray radiation, samples of sensitive film were used, located on the side of discharge gap.

So, nanosecond crown discharge reactor proposed by us was developed on the basis of "pin – plane" electrode system with dielectric nozzles in "wire – cylinder" electrode construction. Potential electrodes with nozzles were installed on conductor, and distances between them were determined experimentally so that discharge zones of neighboring electrodes do not overlap each other.

Figure 2 shows "pin-plane" electrode system with various dielectric barriers located along the axial line of gap. Purpose of such experiments was to determine dependence of influence of various gap and dielectric materials parameters (distance from "pin" electrode to barrier surface - $b$, thickness - $h$, dielectric constant - $\varepsilon$, surface charge density - $\sigma$, dielectric surface state, etc.) on discharge characteristics (current, field strength, branching intensity of streamers, etc.).

Varying distance between "pin" electrode and barrier, as well as parameters of barrier itself, made it possible to empirically determine the optimal branching mode of streamer channels in interelectrode space without converting streamers into spark and minimizing influence of polarization field of charges deposited on dielectric barrier surface on discharge characteristics (current, field strength, size of streamer's head, length and width of discharge zone). These experimental data will need to be considered further in development of high-voltage devices and their individual components, as well as in choice of material for insulating structure.

As noted earlier, in presented article to explain the physical processes occurring during formation of nanosecond pulsed discharge in dense air, we explored at interelectrode distances (3÷15 mm) with various designs of potential "pin" electrode with dielectric nozzles. Metal grid with 1.5 mm pitch was used as an anode. Position of the nozzles is varied relative to each other and the end of electrode in range of 0÷5 mm. Role of porcelain nozzle was to form partial discharges in "pin-porcelain" gap, and flat nozzle of fluoroplastic or plexiglass - to accumulate negative ions on their surface with further decay in strong electric field with generation of free electrons needed to reduce and stabilize the discharge delay time.

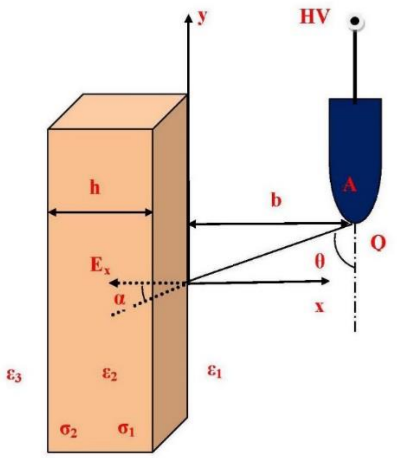



Figure 2. Design of electrode system for excitation of nanosecond crown electric discharge in presence of dielectric barrier: $b$ is distance between "pin" electrode and dielectric barrier; $h$ is thickness of barrier; $\varepsilon_1$ and $\varepsilon_3$ are air dielectric constants; $\varepsilon_2$ is dielectric constant; $\sigma_1$ and $\sigma_2$ are surface charge density at the "air-dielectric" interface; $\theta$ is angle between axis of gap and segment connecting the center of spherical part of "pin" electrode; $\alpha$ is angle of field vector refraction

## 3. DISCUSSION OF EXPERIMENTAL RESULTS

By varying position of dielectric nozzles and air pressure within 1÷5 atm. We changed conditions for excitation of nanosecond discharge and formation of charged particles stream in interelectrode gap, i.e. provided control the discharge processes there. This is very important on developing energy-efficient crown discharge reactors with optimal development modes for non-overlapping streamer channels. When comparing obtained luminescence areas of discharge gaps for various gap parameters, it was found that presence of bright white luminescence at cathode surrounded by volume diffuse violet halo, corresponding to luminescence of excited nitrogen molecules (second positive band), is common for all observed discharge channels [6].

The white luminescence at the tip of "pin" potential electrode probably corresponds to radiation from the near-cathode plasma with sufficiently high temperature. Discharge glow area in case of porcelain and fluoroplastic nozzles on "pin" electrode with radius of curvature – $r$=1 mm, is much wider than in their absence. Change position of nozzles relative to the end of "pin" and each other within 1÷4 mm, illumination area is expanded even more. So, using only porcelain tube at different positions, luminescence area is increased to 10 mm (2 times), and with fluoroplastic nozzle - to 27 mm (6 times). Changing position of plexiglass nozzle relative to end of "pin" electrode with radius of curvature $r$=4 mm, size of glow area is reached up to 62 mm. With increasing air pressure in working chamber up to 5 atm, luminescence area is expanded even more.

So, in case of "pin" electrode with $r$=1 mm in using only porcelain nozzle with increasing pressure, dimensions of luminescence area are changed from 8 mm at $p$=1 atm to 15 mm at $p$=5 atm, and for "ball" electrode with $r$=8 mm - up to 30 mm.

For more detailed research and understanding of physical processes occurring in near-electrode areas during excitation of nanosecond pulsed discharge, we researched changes on electrodes surface and processes involving high-energy electrons. Research results identified that in process of discharge formation due to presence of high supercritical field at "pin" electrode, microstrike processes occur, leading to autoelectronic emission with generation of high-energy electrons penetrating interelectrode space. Microcraters form at explosion sites, size and number of which also vary depending on radius of curvature of potential electrode.

Figure 4 shows graphs of the microcraters size on potential electrode on medium parameters (working gas pressure) and radius of curvature of electrode.

It can be seen from graphs that dimensions of craters on potential "pin" electrode with $r$=1 mm is increased from 75 µm at $p$=1 atm to 150 µm at $p$=3 atm. Moreover, at low pressures, they are located as small size formations. In case of high pressures, these microcraters look like a single entity. With increase in radius of curvature of potential electrode ($r$=4 mm) at $p$=1 atm., sizes of craters are somewhat smaller compared to $r$=1 mm and are arranged separately - at some distance from each other. Such small dimensions of craters on surface of potential electrode with large radius of curvature are apparently associated with increase in their number on more developed surface and uniform distribution of electric field strength on these craters, which cannot be said of electrodes with small radius of curvature and concentration of all critical field strength on one crater.

Microexplosion processes at a potential "pin" electrode (cathode) lead to generation of high-energy electrons that penetrate entire interelectrode distance and cause brake radiation at anode surface.

High-frequency X-rays are detected both at cathode and anode surface. To record radiation, sensitive photographic film was used, which was placed on the side of centerline of gap. To explore effect of radius of curvature of potential electrode, position of dielectric nozzles and working gas pressure on intensity of X-ray generation, we have conducted numerous researches. Air pressure in gas gap was varied in range $p$=1÷5 atm. Position of porcelain tube on potential electrode was varied relative to its end in range of 1÷5 mm. In some experiments rectangular fluoroplastic and plexiglas nozzles were used, which also moved relative to the end of "pin" electrode.

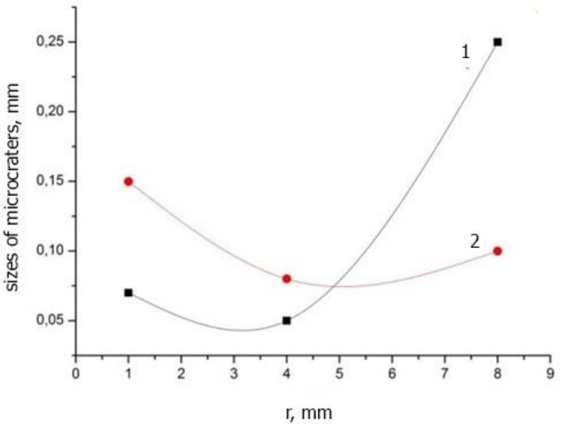


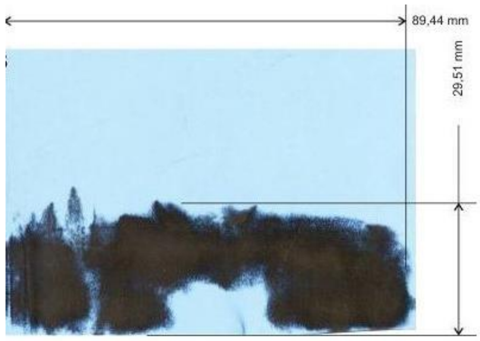

Figure 3. Dependence of microcraters size on potential electrode from its radius of curvature: 1- *p*=1 atm; 2- *p*=5 atm

For each configuration of potential electrode with different dielectric nozzles, nanosecond discharge was excited in gas gap and X-rays were recorded using dosimeter, located to the side of discharge zone at distance ~1 cm. Cassette with new high-contrast blue-sensitive X-ray film, was installed opposite it. X-ray autographs were obtained by continuously following pulses. X-ray registration on photographic films showed that only on negative voltage polarity on "pin" electrode, intensity and energy of X-ray quanta is sufficient to illuminate film in black paper.

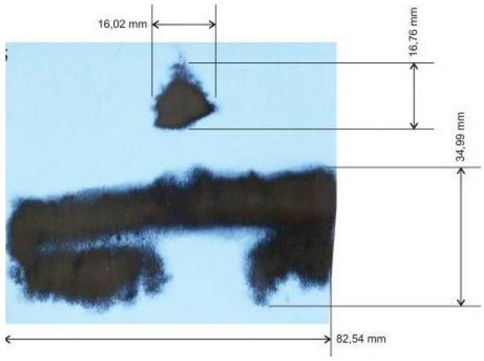
In Figure 4 is shown registration of X-ray radiation at both cathode and anode. From Figure 4, it can be seen that when using "pin" electrode with *r*=1 mm in presence and absence of dielectric nozzles at atmospheric pressure, X-rays are recorded at cathode and anode (Figure 4(c),(d)). In case of "pin" electrode with *r*=4 mm, if there is plexiglas nozzle on "pin" electrode, extended to 5 mm relative to the end of "pin", radiation at atmospheric pressure is recorded only at anode (Figure 4(a)). Increase in air pressure up to 5 atm, even in absence of dielectric nozzle on "pin" electrode, contributes to X-rays at cathode and anode.

As mentioned earlier, in our article in order to develop an energy-efficient nanosecond crown discharge reactor for cleaning harmful industrial gas emissions into atmosphere, the task was also set to optimize efficient discharge initiation modes and to explore discharge structure. For this purpose, dielectric barriers with different geometrical and electro physical parameters at various distances from potential electrode were placed in discharge gap parallel to the gap's axial line and effect of charges polarization field on discharge characteristics was explored. Structure of discharge (dimensions of streamers heads, charge distribution in streamer channel, etc.) was investigated by electrography method.

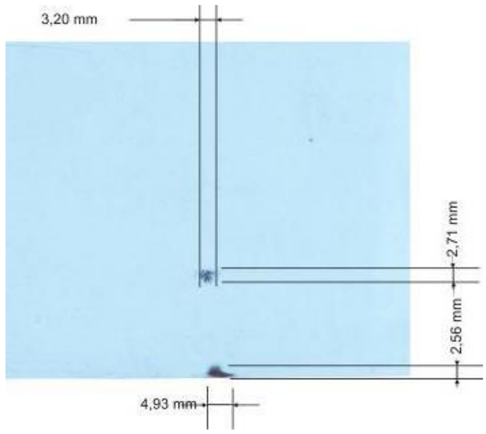
To obtain electrograms, thin dielectric plates of various thickness and dielectric constant were placed at different distances – *b*=0÷5 mm from crown-forming electrode. Before each new experiment, remaining charge was removed from plate's surface by method described in [7].



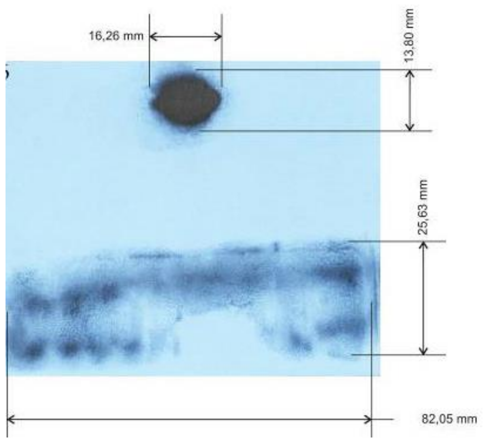

(a)




(b)




(c)




(d)

Figure 4. X-ray autographs for cathodes with different r, in presence and absence of dielectric nozzles, *d*=13 mm (interelectrode distance): (a) "pin" electrode (*r*=4 mm), p =1 atm, plexiglass nozzle is pushed to 5 mm relative to end of potential electrode; (b) "pin" electrode (*r*=4 mm), *p*=5 atm, without dielectric nozzles; (c) "pin" electrode (*r* =1 mm), *p*=1 atm, without dielectric nozzles; (d) "pin" electrode (*r*=1 mm), *p*=1 atm, porcelain nozzle is pushed to 5 mm from the end of potential electrode

For identification of charge deposited on the plate, toner (fine-grained black powder) for laser printers was used. Plates were sprinkled with that powder and then subjected to vibration. When it was inclined, powder slowly moved across the plate surface and settled at the charge locations. It was possible to obtain streamer's branching and analyze parameters of its individual head. When dielectric plate is introduced into discharge gap, conditions for discharge development are changed. Influence degree depends on how barrier is installed.

Exploration of discharge structure should be carried out with such arrangement of plates, in which its influence on discharge characteristics is minimal. Plexiglas dielectric plates by thickness $h$=1.5 mm were installed in three positions relative to potential electrode, at distance - $b$=0 mm, $b$=2.5 mm and $b$=5 mm. When installing plate close to "pin" electrode, discharge current is increased by average of 2 times.

Current reaches amplitude value in less than 5 ns (in purely air gap ~ 35÷40 ns), then exponentially decreases. When installing plate at distance – $b$=5 mm from "pin" electrode, discharge characteristics do not undergo any noticeable changes. However, in this case, only separate streamers reach plate surface and in this case it is difficult to learn something about discharge structure. When installing plate at $b$=2~3 mm from "pin", discharge characteristics are slightly changed (about 10%).

Thus, when using electrography, it is necessary to install plate no closer than 2 mm from crown electrode. Otherwise, there is significant change in discharge characteristics. To assess effect of plate's material, its geometrical and electro physical parameters on discharge characteristics plexiglas and ceramic plates with dielectric constant $\varepsilon_1$=3; $\varepsilon_2$=9 and thickness $h_1$=2 mm; $h_2$=5 mm were used in experiments presence of plate mounted close to "pin" electrode leads to similar change in current, regardless of barrier material. Current amplitude is increased by average of 2 times for plexiglass and 3 times for ceramics. Electrograms make it possible to estimate difference in discharge structure for different materials.

On thicker plexiglass plate, discharge trace has large dimensions than on thin one, and its surface is more densely filled with channels and heads of streamers, especially around perimeter of streamer zone. On ceramics, discharge is 10-20% larger than on plexiglas plate, while intensity of branching of streamer channels is smaller and appear much more clearly than on plexiglas ones. Thus, we can conclude that with increasing thickness and dielectric constant, influence of barrier on discharge parameters is also increased. Therefore, for electrography, it is advisable to use thin (no more than 2 mm) plates with smallest possible - $\varepsilon$.

The high definition of streamers heads and adjacent channels on electrograms made possible to measure their sizes. So, diameter of streamer's head is 100÷150 μm, diameter of streamer channel at ~ 1 mm from head is ~ 150÷200 μm, at 3 mm and further ~ 200÷300 μm. Central part of channel on electrogram is darker than its background. It can be concluded that excess positive charge in streamer channel is unevenly distributed: its concentration is low on streamer axis and increased towards lateral border of channel. It should also be noted that development of streamer zone goes not only along the axis of gap, but also in radial direction.

Moreover, on border of streamer zone there are separate streamers, developed almost perpendicularly to axis of the gap. This indicates high density of streamer channels and large excess charge of streamer heads, which in general results in their significant repulsion. In [8], calculation results are given, showing increase in maximum field strength at crown potential electrode in presence of dielectric plate (Table 1). Table shows that in presence of plexiglas plate with thickness $h$=2 mm, mounted close to "pin" electrode, value of maximum field strength is increased from 630 kV/cm to 690 kV/cm.

Figure 2 shows displacement of the point A with maximum field strength at angle - $\theta$ towards plate, located at distance - $b$ from crown electrode. Point (A) with maximum field strength on the surface of "pin" electrode is shifted so that angle between the axis of gap and segment connecting the center of spherical part of "pin" and point with maximum field strength is ~ 15°. In similar case with ceramic plate, angle of displacement is ~ 30°, and value of maximum field strength is ~ 880 kV/cm. When installing plate at distance – $b$=2.5 mm from the "pin" electrode, its influence on field near crown electrode is very slightly. In case of plexiglas plate, maximum field strength is increased from 630-638 kV/cm, with ceramic plate – up to 680 kV/cm. Angles of displacement of point A with maximum field strength are, respectively, 4° and 12°.

Table 1. Effect of dielectric barrier on value of maximum field strength at crown electrode

| Calculation Parameters | $E_{max}$, kV/cm | $\alpha$, degree |
|---|---|---|
| Gap without plate | 630 | 0 |
| Plexiglas plate, $h$=2 mm, $b$=2.5 mm | 638 | 4 |
| Plexiglas plate, $b$=2 mm, $b$=0 mm | 690 | 15 |
| Plexiglas plate, $h$=5 mm, $b$=2.5 mm | 800 | 24 |
| Ceramics, $h$=2 mm, $b$=0 mm | 880 | 30 |
| Ceramics, $h$=2 mm, $b$=2.5 mm | 680 | 12 |

Maximum field strength in this case is 800 kV/cm, and angle of displacement of the point with maximum intensity is ~24°. It should be noted that almost always in branching areas of streamer, main channel is curved. This happens regardless of where considered streamer is developed: at front of streamer zone, at the side or near discharge electrode. This gives grounds to assume that streamer branching occurs at its head and charge field of branched streamer bends trajectory of main streamer. It was revealed that during streamer 's development along plate surface is affected by polarization field of plate, which leads to increase in its transverse size.

In addition, account should be taken of charge spreading over plate surface, which can also lead to increase in transverse size of developed traces of streamer head and channel. Increase in dielectric thickness leads to both increase in field at crown electrode and in polarization field of barrier, which affects streamers developing along its surface. Therefore, with increasing barrier thickness, discharge current amplitude and branching intensity of discharge surface part is also increased.

## 4. CONCLUSIONS

Thus, in present article, complex researches were carried out to optimize excitation modes and development of nanosecond crown discharge in dense air (at atmospheric pressure and above), to explore discharge structure and its components, stabilize discharge formation processes, develop innovative designs of potential electrodes using dielectric nozzles to control flow of high-energy charged particles and force fields in interelectrode gap, etc. All these researches were carried out for developing energy-efficient working chambers and crown-type reactors for use in process of cleaning harmful gas emissions.

Conducting research on effect of location of dielectric nozzles on potential electrode on excitation and formation processes of nanosecond discharge revealed that using both types of nozzles (fluoroplastic and porcelain) improves conditions for initiating discharge with short delay time (units of nanoseconds) due to formation of negative ions and their accumulation on the surface of hydrophobic fluoroplastic nozzle and their further decay in strong electric field with generation of free electrons. Due to this, noticeable expansion of excitation zone of discharge in radial direction up to 70 mm was achieved. Exploration of discharge structure and its individual components (streamers head's size, discharge channel) using electrographic method allowed us to determine the optimal conditions for formation of volume nanosecond discharge when its characteristics (current, field strength, etc.) undergo slight change in presence of various dielectric structures in construction.

It was found that with minimum average field strength ~ 8 kV/cm in discharge gap, it is possible to ensure stable formation of streamer channels and their active branching. This, in turn, will lead to maximum generation of reactive discharge products (ozone, atomic oxygen), which are directly involved in process of neutralizing toxic gas emissions. On the other hand, during formation of volume nanosecond crown discharge under appropriate conditions, discharge zone is expanded in both longitudinal and radial directions. Considering that potential electrodes are located in the same plane in reactor design, one of important moments in formation of crown discharge is do not allow overlapping of discharge zones of neighboring gaps. As a result of research on discharge structure, it was found that width of discharge zone is increased in range of 60÷70 mm. Given that excitation zone of nanosecond discharge is also increased within these limits, identical potential electrodes with nozzles in reactor were located at distance ~70 mm from each other. Their number can be adjusted depending on performance of industrial enterprise.

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## BIOGRAPHIES

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