CONDITIONS FOR THE EMERGENCE OF POSITIVE STREAMER CORONA DISCHARGE IN AIR IN THE NEEDLE-TO-PLANE ELECTRIC FIELD

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The features of the positive streamer corona discharge are the long length and the duration of each streamer. They define this type of discharge as one of the alternative paths of potential technological application and characterize the relevance of research in this direction. The aim of the work is to determine the influence of the geometric characteristics of the needle and the voltage between the electrodes to the size of the areas, the beginning of the development of electron avalanches from which leads to their transformation into a streamer form of corona discharge in air at atmospheric pressure. For electrode systems with needles in the form of hyperboloid and paraboloid of rotation, sphere and 10.15407/long cylinder, the electric field distribution is considered and the volume of the areas where the appearance of effective initial electrons leads to their multiplication to the stage of avalanche-streamer transition in the strongly inhomogeneous electric field is determined. It is established that the size of the specified volumes, in addition to the curvature radius of the tips, is significantly affected by the shape of the electrode outside the part of its surface with the smallest radius of curvature. It is shown that despite the smaller values of the maximum field for the hyperbolic needle, here the volume of the appearance of effective initial electrons can exceed the volume for cylindrical and even more so for spherical electrodes of the same tip curvature radius at the same value of voltage. A feature of the long cylindrical needle is the extension of the start zone of the effective electrons over a considerable distance along the cylindrical surface of the electrode. From the comparison of different electrode systems, it was concluded that the choice can be made according to the magnitude of the volumes of appearance of effective electron, as a quantitative indicator that takes into account the needle configuration, tip radius, and value of voltage. References 24, figures 6.
Key words: positive streamer corona, needle-to-plane electric field, avalanche-streamer transition, streamer emergence efficiency indicator.

Introduction. Among the numerous applications of electric discharge in gas, corona discharge is still important today. The attractiveness of this type of discharge lies in the efficiency of creating electrically charged and chemically active particles: particle charging is carried out by ions generated in corona discharge and drifting in the electric field; energetic electrons and photons generated in the corona discharge are used to carry out electrochemical reactions to produce active radicals, such as HO, NOx, O_3, and others, which are effectively used to decompose harmful impurities in gases and liquids [1, 2]. Currently, comprehensive studies of corona discharge in gases have been carried out, a detailed review of which is reflected, in particular, in [3, 4].

Two forms of corona discharge – avalanche and streamer – have found application in various technological processes and devices. A special area of use of corona discharge is the production of ozone from oxygen-containing gases [5]. The use of streamer corona discharge in ozone generators, which attracted attention after the avalanche discharge, allows for increased reliability of the process and economic efficiency [6]. Studies have shown that the use of positive corona (with a positive potential of the corona electrode) gives a higher yield of chemically active particles. This is related to the feature of the development of a positive streamer corona and is due to the high electric field strength $\approx (150-170)\cdot 10^5$ В/м in the streamer head [7], which can significantly exceed the breakdown strength of the gas in a homogeneous field.

Compared to the barrier discharge [8-10], which, in particular, shows high efficiency in ozone generation, the corona discharge has a number of important features. The gap between the electrodes in barrier systems does not exceed a few millimeters. The corona discharge develops in a volume with much larger dimensions, the streamers have a much greater length and each of them exists for a longer time compared to streamers in the barrier discharge [11]. Increasing streamer density is achieved by using a system with a large number of electrodes from which streamers develop. So, the features of streamer corona discharge define it as one of the alternative paths of potential technological application. The study of the development of the streamer process in a sharply inhomogeneous field created by electrodes with a small radius of curvature is important not only for understanding the electrophysical processes that accompany the streamer discharge. This ultimately allows for purposeful selection of the parameters of the electric discharge system to obtain the necessary characteristics of technological processes.

The **aim** of the work is to determine the influence of the geometric characteristics of the needle, which forms the distribution of the sharply inhomogeneous electric field, and the voltage between the electrodes on the size of the areas, the beginning of the development of electron avalanches from which leads to their transformation into a streamer form of corona discharge in air at atmospheric pressure.

The development of the streamer process from the beginning of the growth of the electron avalanche to the transformation of the avalanche into streamer is considered. This process is analyzed in a system with a single electrode in the form of the needle, which can have a different configuration and curvature radius of the tip. It is assumed that electroionization processes take place in the electric field formed in the gap without taking into account the volumetrically distributed charge of ions. This mathematical model most closely corresponds to the processes when a single rectangular pulse is applied to the electrode system. The approximate mathematical model is often used in the investigation of the avalanche stage of the electric discharge development also for other dependences of voltage in time [7], including, under certain assumptions, a constant voltage. In the text, the term "needle" refers to a thin long electrode, which can have a different shape of the lateral surface and end with a tip of the smallest curvature radius.

Growth of the electron avalanche and the condition for its transformation into streamer. Corona is a low-current discharge that appears in the strongly inhomogeneous electric field in an area where the field is sharply enhanced, for example near the needle, wire, etc. Fig. 1, *a* shows an electrode system in the form of the needle with positive potential opposite a conducting body with flat surface. A feature of ionization processes in the sharply inhomogeneous field is that they take place in a relatively narrow region near the electrode and in the head of the streamer, where the field strength has a maximum value, and in the rest of the gap there is no ionization, there is only charge drift. The positive corona may have a streamer shape, which manifests itself as filamentary channels. In any case, an avalanche form of electron propagation, where the main mechanism is impact electron ionization of neutral molecules, precedes the appearance of streamers. To transform the avalanche into streamer, certain conditions must be met under which the electric field of the electron avalanche reaches the required value [12].

In electronegative gases, which include air, in addition to ionization, electrons attach to molecules. Both processes are characterized by ionization α and attachment η coefficients, respectively (number of ionization or attachment events when an electron moves in the electric field over a distance of 1 m). These coefficients depend on the electric field strength, the empirical functional dependences of which are presented, for example, in [7, 13, 14]. The threshold value of the ionization process is determined by the condition when the ionization coefficient α begins to exceed the attachment coefficient η. For air, the presence of oxygen in which determines its electronegative properties, the ionization and attachment coefficients are equalized at the ratio of the field strength to the gas pressure $E/p \approx (26-31)\,\text{V}/(\text{m}\cdot\text{Pa})$. In the calculations we will use one of the most common approximations of experimental data for the effective ionization coefficient $\alpha_{ef} = \alpha - \eta$

$$\frac{\alpha_{ef}}{p} = A\exp\left(-\frac{B}{E/p}\right), \tag{1}$$

where p is pressure, the coefficients A and B in the SI system in discharges in air have the following values [7, 14]:

$E/p = 15-114\,\text{V}/(\text{m}\cdot\text{Pa})$: $A_1 = 6.46\ 1/(\text{m}\cdot\text{Pa})$, $B_1 = 190\,\text{V}/(\text{m}\cdot\text{Pa})$;

$E/p = 114-600\,\text{V}/(\text{m}\cdot\text{Pa})$: $A_2 = 11.1\ 1/(\text{m}\cdot\text{Pa})$, $B_2 = 277.4\,\text{V}/(\text{m}\cdot\text{Pa})$.

When a voltage of the required magnitude is applied, the avalanche of electrons (Fig. 1, *b*) moves in the electric field with the electron drift velocity $v_e = \mu_e E$, where μ_e is the electron mobility. The number of electrons N_e in the avalanche increases exponentially [15]:

$$N_e(\xi) = \exp\left(\int_{\xi_0}^{\xi} \alpha_{ef}(\xi) d\xi\right). \qquad (2)$$
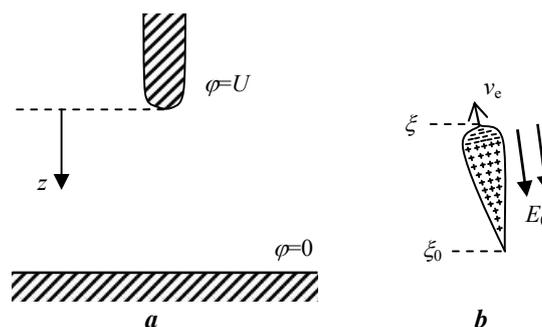

Fig. 1

Here, the value of the effective ionization coefficient in the electric field that varies in space depends on the position of the point in space $\alpha_{ef}(E(r))$. In expression (2), the coordinate along which the avalanche of electrons moves is denoted by ξ (usually this is a field line). The avalanche of electrons moves, increasing from the position ξ_0 of the initial electron. If the movement of the avalanche is carried out along the axis z – the smallest distance between the electrodes, then replacing the coordinates in expression (2) it is necessary to take into account the opposite direction of the coordinates ξ and z in Fig. 1.

During the ionization of neutral molecules, positive ions are formed simultaneously with electrons, and in electronegative gases, negative ions are also formed. The mobility of ions is much lower than the mobility of electrons, and during the movement of the avalanche of electrons, ions can be considered motionless. The numbers of positive N_+ and negative N_- ions in the avalanche trace at a point with the coordinate ξ are as follows:

$$N_+ = \int_{\xi_0}^{\xi} \alpha N_e d\xi, \quad N_- = \int_{\xi_0}^{\xi} \eta N_e d\xi. \qquad (3)$$

The charge of the avalanche creates its own electric field, which is superimposed on the external field of the electrode system. The total field near the avalanche of electrons increases in the direction of electron motion and, conversely, decreases in the opposite direction. The volume distributed charge of ions also creates its own electric field, but due to its certain distance from the avalanche head and lower concentration in space, its effect to the electric field near the electron avalanche is smaller compared to the field of the electron avalanche. For this reason, we will neglect the electric field of ion charge at the avalanche stage of the electric discharge process.

In a strongly inhomogeneous field, the ionization zone is limited by a boundary where the electric field strength drops to a critical value E_i, which is determined by the achievement of the condition of no ionization at the corresponding points r_i in space:

$$\alpha_{ef}(E_i) = 0. \qquad (4)$$

With a positively charged needle, the movement of the electron avalanche is directed from the outer area to the needle in the direction of increasing field. Therefore, condition (4) defines the limit beyond which free electrons will not lead to ionization and, accordingly, the appearance of electron avalanches.

In sharply inhomogeneous field, more often near an electrode with small radius of curvature, the energy gained by an electron over the mean free path may exceed the energy given off in inelastic collisions. In this case, the electrons enter the continuous acceleration mode or otherwise there is "electron escape". In [16] it is shown that there is an upper limit of the electric field strength E_a for the transition of the usual form of discharge to the continuous acceleration mode, starting from which the ionization coefficient decreases with increasing field. The field strength estimate E_a in [13] was made based on the maximum value of the electron braking force [17] $F(W_e) = \dfrac{e^4 n_0 Z}{8\pi\varepsilon_0^2 W_e}\ln\left(\dfrac{2W_e}{I}\right)$ with respect to the average electron energy W_e, where e is the electron charge, n_0 is the number of gas molecules per unit volume, Z is the number of electrons in a molecule, I is the average energy of inelastic electron losses. The force $F(W_e)$ at $W_e = I/2$ takes on a

maximum value, which gives the magnitude of the critical electric field $E_a = \dfrac{F(I/2)}{e} = \dfrac{e^3 n_0 Z}{4\pi \varepsilon_0^2 \exp(1) I}$. Starting from E_a the energy of electrons can only increase. For nitrogen at atmospheric pressure and temperature $0^0\,\mathrm{C}$ $\left(Z = 14, I \approx (75-80)\,\mathrm{eV}, n_0 = 2.69 \cdot 10^{25}\,\mathrm{m}^{-3}\right)$, the critical field strength is found to be $E_a \approx 450 \cdot 10^5\,\mathrm{V/m}$. For oxygen, we obtain a similar value.

Beyond the specified values of the field strength, the correctness of using avalanche or streamer models of electric discharge development is hardly justified. That is, the area of study of ionization processes before the appearance of streamers can be limited both from the outside by the ionization boundary and near the tip of the needle when the field reaches the limit of electron continuous acceleration.

H. Röther, A. Loeb, and J. Mick in the middle of the last century laid the theoretical and experimental foundations of the development of the streamer process [18 – 20]. During the following period, the concept of the electric discharge and its streamer form received significant development [7, 13].

It is believed that the condition for the avalanche-streamer transition is achievement the electric field strength of the electron avalanche charge a value E' that is approximately equal to the magnitude of the field of the external source E_0:

$$E' \approx E_0. \tag{5}$$

The electric field strength at the surface of the avalanche created by avalanche charge is primarily determined by two factors: the number of electrons N_e in the avalanche and its size. In each avalanche, as electrons move in the electric field and the number of electrons increases, the diffusion of electrons and its electrostatic repulsion take place [7]. At the initial stage, the size of the avalanche is determined by the diffusion process. As the avalanche grows, the repulsion process begins to take precedence. At this stage, the growth of the avalanche size is limited by the oppositely directed forces between the electrons and positive ions. Approximately the maximum radius of the electron cloud is determined by the condition when it is equal to the ionization length $R_e \sim \alpha_{ef}^{-1}$. In the stationary electric field, the process of electron repulsion determines the final size of the avalanche and, accordingly, the electric field at its surface.

Using the model of the electron avalanche in the form of a charged sphere, which is often used in theoretical models, condition (5) taking into account (2) can be rewritten as:

$$E' = \frac{e}{4\pi\varepsilon_0 R_e^2} N_{es} = \frac{e}{4\pi\varepsilon_0 R_e^2} \exp\left(\int_{\xi_0}^{\xi_s} \alpha_{ef}(\xi)\,d\xi\right) \approx E_0, \tag{6}$$

where N_{es} and ξ_s are, respectively, the number of electrons in the avalanche and the coordinate where the avalanche-streamer transition condition is satisfied, ε_0 is the electric constant.

Processing a significant amount of experimental data for data at atmospheric pressure in the stationary field gives the following critical value of the following parameter:

$$Q = \ln(N_e) \approx 20. \tag{7}$$

This value Q in (7) is consistent with the data in the works of A. Loeb and J. Mick, where the radius of the avalanche was taken as the radius at which, due to the diffusion of electrons, their density decreases by a factor of $\exp(1)$ compared to the density in the center of the avalanche. In this case, the avalanche-streamer transition occurs at $Q \approx 18 - 20$ and $N_{es} \sim 10^8$, respectively. At the same time, as noted in [7], a different way of choosing the avalanche radius R_e has a weak effect to the value of the parameter Q.

The existence of ionization does not necessarily lead to the fulfillment of conditions (5) or (7) of the avalanche-streamer transition. The appearance of the streamer in a certain area is possible if for any trajectory of avalanche movement (field lines) in this area the avalanche moves the required distance for which condition (5) or (7) is fulfilled. Denoting the coordinate along the trajectory of avalanche movement as ξ, the condition for the appearance of the streamer in the area can be represented as follows:

$$\int\limits_{\xi_i}^{\xi_a} \alpha_{ef}(\xi)d\xi \geq Q, \qquad (8)$$

where the integration extends over the entire field line from a point on the boundary of the ionization area ξ_i to the electrode ξ_b or to the boundary of the area of continuous electron acceleration ξ_a.

The fulfilling the streamer appearance condition (8) also determines the coordinates ξ_k of surface corresponding to the minimum possible distance to the needle. The coordinates ξ_k correspond to the position of the initial electron for which the avalanche transforms into the streamer at the extreme point of motion, i.e. reaching the positive electrode or the boundary of the area of continuous electron acceleration. The initial electron appearing in the area between ξ_i and ξ_k initiates the development of the avalanche to the size when it transforms into the streamer.

Ionization zones and emergence of the streamer in the needle-to-plane electric field. Since the field strength near the needle is significantly higher than the field in the rest of the gap, it is here that the main electrophysical processes of the electric discharge in gas take place, in particular: ionization of neutral molecules, increase and movement of electron avalanches, transformation of the avalanche to streamer and its growth to the opposite electrode, as well as excitation of molecules, photon emission, plasma chemical processes associated with the electric discharge. The main parameter that determines the value and distribution of the sharply inhomogeneous electric field of the needle against the plane are the ratio of the radius of curvature of the needle tip to the distance between the electrodes (in the case of a rounded tip), as well as the average field strength and the configuration of the needle outside the part of its surface with the smallest radius of curvature. From this point of view, we will consider the electric field of several typical configurations of the needle mainly in the area near the tip of the needle.

The electric field of the needle of different configuration. First, we will consider how different the electric field distributions near the needle of following geometric shape: hyperboloid and paraboloid of rotation, sphere, and long cylinder. This question is important for modeling electrophysical processes in the sharply inhomogeneous field.

The geometry of the needle in the form of the hyperboloid (Fig. 2, a) and paraboloid (Fig. 2, b) of rotation is described by analytical expressions containing the values of the minimum radii of curvature at the peak r_c and the distance d between the electrodes [21]:

$$\frac{(d-z)^2}{d^2} - \frac{\rho^2}{r_c d} = 1, \quad z = -\frac{\rho^2}{2r_c}, \quad (z \leq 0), \qquad (9)$$

where the coordinate z is counted from the peaks of the needle, ρ is the distance from the axis of symmetry in the radial direction. The geometry of the needle that usually used in experiments has a cylindrical form (Fig. 2, c). We will assume that the tip of the needle has the shape of a hemisphere of the same radius as the cylindrical part. This assumption is justified if we consider the electric field at a distance from the tip that exceeds the characteristic size that equal to the radius of cylinder.

In the figures equal radii of curvature of the tips are chosen. They are shown as spheres of the corresponding radius. Near the tips, the geometry of the needles differs slightly, but becomes noticeable when moving away from it.

The electric field strength on the axis of symmetry of the gaps reaches the highest values at the surface of the tip, but also decreases rapidly with distance from it. The expressions for the field with the needles of hyperboloid $E_g(z)$ [22] and paraboloid $E_p(z)$ [7] types depending on the coordinate z have a simple analytical form, which allows us to obtain a clear conception
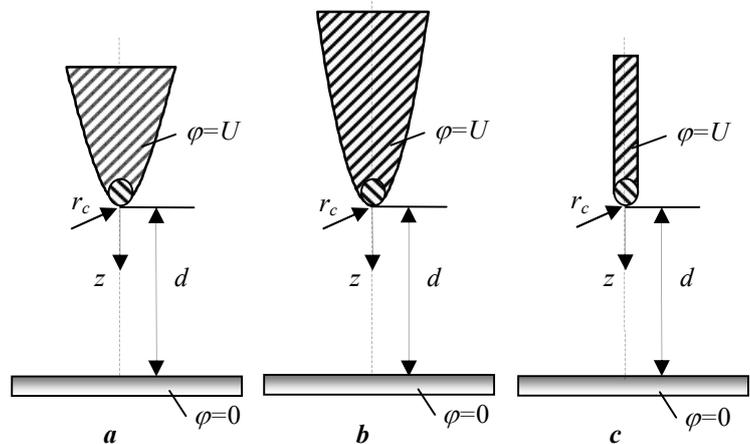

Fig. 2

of the electric field distribution:

$$E_g(z) = U \frac{\sqrt{d^2 + r_c d}}{r_c d + 2dz - z^2} \frac{1}{\text{Arth}\left(\dfrac{d}{\sqrt{d^2 + r_c d}}\right)}, \qquad E_p(z) = U \frac{2}{(r_c + 2z)\ln\left(1 + \dfrac{2d}{r_c}\right)}. \qquad (10)$$

For the sphere-plane electrode system, the exact dependence of the field strength distribution along the axis z cannot be represented by simple expressions. However, for the ratio values $d/r_c \leq 100$, it is possible to use the expression that gives an error at the surface of the sphere that does not exceed 0.5% at small ratios and error decreases with the ratio d/r_c increases [22]:

$$E_r(z) = U \frac{2d\left[d^2\left(E_{rm}^* + 1\right) + (d-z)^2\left(E_{rm}^* - 1\right)\right]}{\left[d^2\left(E_{rm}^* + 1\right) - (d-z)^2\left(E_{rm}^* - 1\right)\right]^2}. \qquad (11)$$

Here, the normalized magnitude of the electric field strength $E_{rm}^* = \dfrac{E_r(z = 0)}{U/d}$ at the surface of the needle

has a maximum value and it is the coefficient of heterogeneity:

$$E_{rm}^* = \frac{1}{4}\left[\frac{2d}{r_c} + 1 + \sqrt{\left(\frac{2d}{r_c} + 1\right)^2 + 8}\right]. \qquad (12)$$

The calculation of the field strength for electrode system containing the needle in the form of cylinder with hemispherical tip was performed here and further by a numerical method using the COMSOL mathematical package.

The dependence of the maximum magnitude of the field strength at the peak of the needles on the ratio of the maximum electrode curvature to the size gap r_c/d is shown in Fig. 3, a. From the comparison of the maximum electric field strength for the needles of different shape, it follows that modeling the needle with the spherical electrode, the radius of which is equal to the minimum curvature radius of other configurations, can lead to an error reaching 100%, in the direction of increasing the field for the spherical electrode. It should be noted, however, that the situation will be the opposite for another model, when an isolated conducting body located in an external electric field. Here, with an increase in the length of the body the electric field strength will increase at the point where the radius of curvature is minimal. So, despite the fact that the model with an isolated sphere is quite simple, the feasibility of its application must be justified in specific cases.

The peculiarity of the decrease in the electric field strength near the needle with distance from it is shown in Fig. 3, b for the same needle configurations. The greater the maximum field strength at the needle tip, the faster the field decays with distance from it. At the same time, under the condition $r_c \ll d, z \ll d$ the parameter r_c/d has practically no effect to the values E/E_m of the corresponding needle configurations. The field strengths for the needle of hyperbolic and parabolic shapes differ to the smallest extent. For these configurations, the maximum value of the field strength at the needle surface also differs little. Under such conditions, from (10), the field strength for these two types of needle have the values $E_{gm}^* \approx 2/\ln(4d/r_c)$ and $E_{pm}^* \approx 2/\ln(2d/r_c)$. Their difference at $d/r_c \gg 1$ is relatively small, it does not determine significant changes in the development of electrophysical processes, and therefore, in the following we will consider the configuration of only one, hyperbolic, type.
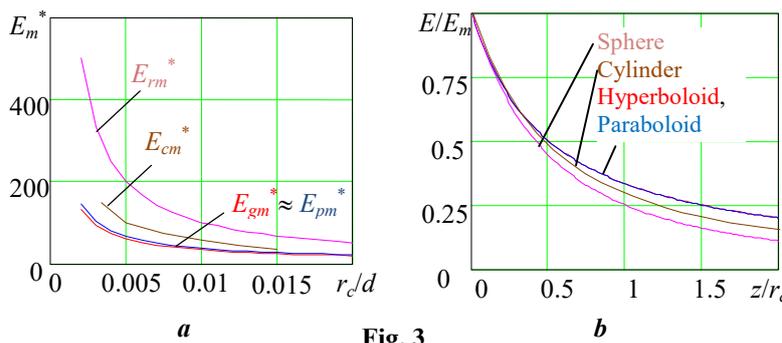
Parameters of ionization processes in the electrode systems. When applying high voltage, the distance to the boundary where the electric field strength exceeds the value of the onset of ionization processes in air at atmospheric pressure $E_i \approx 26 \cdot 10^5 \, \text{В/м}$ can signifi-

Fig. 3

cantly exceed the radius of needle tip r_c. As an example, consider electrode systems with the following specific dimensions: $d = 15 \cdot 10^{-3}\,\text{m}$, $r_c = 5 \cdot 10^{-5}\,\text{m}$, which correspond to values that can be used in experiments [23]. We will assume that the voltage between the electrodes is $U = 17\,\text{kV}$.

From the results presented in Fig. 3, *a* it follows that for the selected parameters at the surfaces of all the needle tips the electric field strength exceeds the continuous acceleration limit of electrons, which we will take equal to $E/p = 450\,\text{B}/(\text{m} \cdot \text{Pa})$. The distances from the surfaces along the vertical axis, on which the field reaches the limit, are insignificant. They turn out to be as follows: $\Delta z_g \approx \Delta z_p \approx 0.57 r_c$; $\Delta z_c \approx 0.86 r_c$; $\Delta z_r \approx 1.8 r_c$.

The electric field strengths at more distant points on the axis are shown as continuous curves in Fig. 4, *a*. The points marked with " **x** " on the curves show the distances from the needle tips to the points where the strength is equal to the ionization limit in air $2.6 \cdot 10^6\,\text{V/m}$. It can be seen that the point farthermost from the tip is the point on the axis z for the hyperboloid of rotation ($z_{ig} = 9.27 \cdot 10^{-4}\,\text{m}$), the intermediate position is occupied by the needle of the cylindrical shape ($z_{ic} = 7.33 \cdot 10^{-4}\,\text{m}$), and the closest point is the point on the axis for the spherical electrode ($z_{ir} = 5.22 \cdot 10^{-4}\,\text{m}$).

Analysis of the appearance of streamers in corona discharges, similar to [24], will be carried out on the basis on the influence of the distribution of a sharply inhomogeneous field on the characteristics of the avalanche stage of the discharge from the start of ionization to the fulfillment of the avalanche-streamer transition condition. If the initial electron appears at a distance z_i, the farthest from the needle where ionization is possible, then the condition (7) of the avalanche-streamer transition is fulfilled at the points marked with the labels " **o** " on the curves in Fig. 4, *a*.

Initial electrons can randomly appear at any point in the gap, but only those electrons will lead to the creation of a streamer that will pass the required growth path, at the end of which condition (7) will be fulfilled. We will assume that the endpoint of the avalanche increase is the point at which the field strength reaches of the continuous of electron acceleration limit $450\,\text{V}/(\text{m} \cdot \text{Pa})$ or electrode surface at lower field strength. The positions of the initial electrons, where the avalanche-streamer transition takes place at such endpoint are marked on the curves as " $\square$ ". Their coordinates are as follows: for the hyperboloid needle $z_{kg} = 0.71 \cdot 10^{-4}\,\text{m}$; for cylindrical needle $z_{kc} = 0.95 \cdot 10^{-4}\,\text{m}$; and for sphere $z_{kr} = 1.28 \cdot 10^{-4}\,\text{m}$.
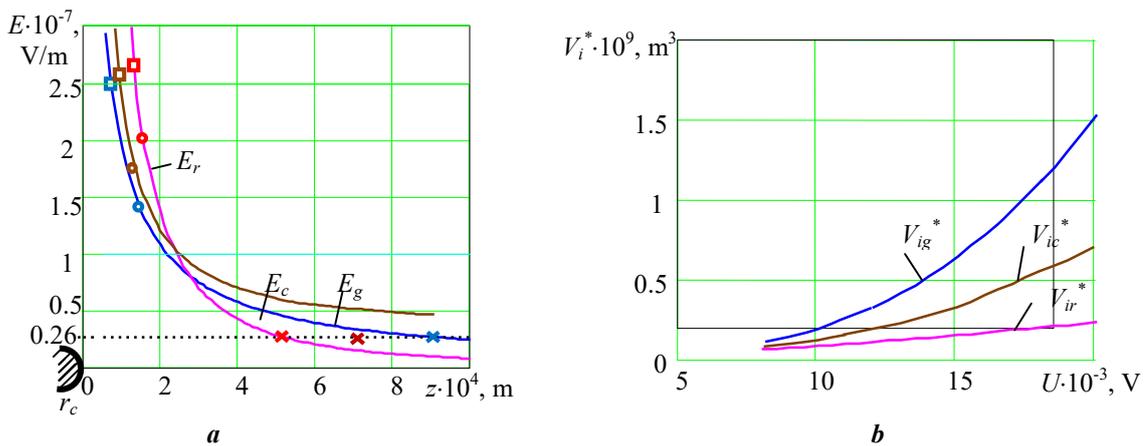

Fig. 4

As can be seen from the presented data, the intervals $z_i - z_k$, where the appearance of initial electrons leads to transformation of growing avalanches to the streamers differ significantly for different needle configurations. Therefore, the question arises about the configurations for which the initial electrons are more likely to appear during the same time. It is also useful to obtain an estimate of the indicator that allows us to compare configurations.

Such indicator can be the value of volume V_i, where the appearance of effective initial electrons leads to the development of avalanches and their transition to the streamer form. The volume V_i is limited on

one side by the boundary of the ionization zone, where the field strength takes the value $E(\xi_i) = 26 \cdot 10^5 \, \text{V/m}$, and on the other – by the surface, starting from which electrons multiply and at the surface of the needle or when reaching the limit of continuous acceleration, the number of electrons in the avalanche reaches the value $N_e = \exp(Q)$ at $Q = 20$. These boundaries are determined by the distribution of the electric field near the needle, which primarily depends on its configuration, tip radius, and the voltage between the electrodes.

In this study, we will assume that the avalanche growth and drift of the electron occur in the electric field of the electrode system. This assumption of neglecting the field of the distributed charge of ions is often used in the study of alone avalanches and streamers. From the assumption that the initial electron can appear with equal probability at any point in the volume V_i, it follows, that this volume is also indicator of the probability of the development of the avalanche and it transition to the streamer form. Then, for the needle configurations under consideration, the probability ratio will be equal to the ratio of the corresponding volumes $V_{ig} : V_{ic} : V_{ir}$.

In this case, we will consider only the areas with the highest field strength near the surface with the smallest radius of curvature. Since the areas where effective electrons appear are close to the surface of the needle, we will estimate the values of the corresponding volumes as the volumes of spherical layers bounded by a certain solid angle Ω. Then each of the volumes will be $V_i = \frac{\Omega}{3}\left[(r_c + z_i)^3 - (r_c + z_k)^3\right]$. Assuming the angle Ω to be the same for all needles with the same radii of curvature $r_c = 5 \cdot 10^{-5} \, \text{m}$, at the voltage 17 kV and distance $d = 15 \, \text{mm}$ we will obtain the following ratio of volumes normalized to a unit value for the hyperboloid of rotation $(V_{ig} : V_{ic} : V_{ir}) = (1 : 0.46 : 0.20)$. Approximately the same ratio between the volumes is maintained when applying the voltage other than 17 kV.

Fig. 4, b shows the dependences of the normalized volumes $V_i^* = 3V_i / \Omega$ on the voltage between the electrodes for the previous values of the distance between the electrodes and of the curvature radii of needle tips. Since in this example $r_c, z_k \ll z_i$, and the distance z_i to the boundary of the ionization zone is proportional to the value of the applied voltage, the volumes increase with increasing voltage as $V_i \sim U^3$. For the minimum voltage $U = 7.5 \cdot 10^3 \, \text{V}$ the average electric field strength $U/d = 5 \cdot 10^5 \, \text{V/m}$ is still sufficient for the streamers to reach the cathode. In this case, the volume is very small and does not exceed a tenth of a cubic millimeter. Note that with the specified ratio of distances $r_c, z_k \ll z_i$ the deviation of the shape of the electrode tips from the taken into account will not lead to a change in the results for the volumes V_i.

It should be noted that the volume size, the appearance of the electron in which leads to the generation of streamer, can also be the indicator for choosing the voltage, needle configurations and their geometric parameters. So, at the radius of the needle tip $r_c = 5 \cdot 10^{-5} \, \text{m}$, the distance between the electrodes $d = 15 \cdot 10^{-3} \, \text{m}$, and voltage 17 kV the best configuration is the hyperboloid of rotation, the field of which on the needle surface is the smallest among those considered and which decreases most slowly with distance from the needle. However, this conclusion is valid with the selected parameters and the assumptions made, the main one of which, in our opinion, is the neglect of the electric field of the distributed charge of ions.

We will analyze the influence of the curvature radii of the needle tips and the voltage between the electrodes on the possibility of streamer formation within certain limits of changing these parameters at the distance between the electrons $d = 15 \, \text{mm}$. Minimum voltage limits the value $U = 7.5 \, \text{kV}$ that ensures reaches to the cathode by the positive streamer. The maximum value should not exceed the spark breakdown voltage, which has order $20 \, \text{kV}$. The maximum radius of curvature of the needle tip is limited by the need to create the streamer corona discharge $r_c / d < 0.1$ [7]. The calculation results of the volume $V_i^* = 3V_i / \Omega$ for the needle in the shape of the hyperboloid of rotation compared to the spherical electrode are shown in Fig. 5.

The first of the figures (Fig. 5, a) shows that the advantage of the needle of the hyperbolic configuration over the system with spherical electrode is limited by a certain value of the curvature radius of the tip. With its increase, a smaller value of the field near the hyperbolic needle leads to the approach of the boundary of the

avalanche transition into the streamer $Q = \ln(N_e) = 20$ closer to the needle surface. The closer this boundary is to the needle surface, the smaller the area from which effective electrons can start.

For each voltage value, there is an upper limit value of the curvature radius of the needle tip, when the growth of the electron avalanche ceases to lead to the appearance of the streamer. Such limit occurs for both hyperbolic and spherical electrode configurations. However, as can be seen from the comparison of the dependences in Fig. 5, *b* and 5, *c*, the limit curvature radii for the spherical electrode are much larger than for the hyperbolic one.

Another aspect of the considered feature of the development of the positive streamer in the sharply inhomogeneous electric field is the existence of a lower voltage limit, the value of which depends on the curvature radius. Fig. 5, *d* shows the dependence of volumes on voltage at different curvature radii of the tip of the hyperbolic electrode. The larger the curvature radius, the greater the limiting voltage value. For the distance $d = 15\,\text{mm}$, the limiting voltage increases to $U = 12\,\text{кВ}$ with increasing curvature radius to $r_c \approx 0.3\,\text{mm}$. For the curvature radius of the hyperbolic needle and for the spherical electrode of arbitrary radius, the limiting voltage value is absent in the range $U/d \geq 5 \cdot 10^5\,\text{V/m}$.

Regarding the influence of a possible deviation of the tip shape from the considered one, it should be noted that near the limit values of the parameters, the character of the dependences of the volumes V_i^* on the voltage and the curvature radii may differ somewhat from those determined. However, this will not affect the presence of limit values and the dependences of the volumes V_i^* when the parameters are removed from the limit values.

If for the distance $d = 15\,\text{mm}$ the voltage does not exceed the value $U = 12\,\text{kV}$ when there is no spark breakdown, then the electrode in the form of the hyperboloid of rotation has the larger volume of appearance of the effective electron for the curvature radii $r_c \leq 0.17\,\text{mm}$. That is, the feasibility of using the electrode of specific configuration depends on the size of the curvature radii of their tips.

Ionization processes for the cylindrical needle. The needle in the form of the cylindrical electrode with hemispherical tip has intermediate characteristics of the electric field distribution between considered hyperbolic and spherical configurations. For this system, let's consider another feature that is characteristic of extended high-voltage electrodes. It concerns the distribution of the electric field strength in the area surrounding the electrode, including its lateral surface.

For the cylindrical electrode with geometric parameters $d = 15 \cdot 10^{-3}\,\text{m}, r_c = 5 \cdot 10^{-5}\,\text{m}$ at voltage of $U = 17\,\text{kV}$ in Fig. 3 the electric field distribution is shown only along the axis z near the needle. For the voltage $U = 10\,\text{kV}$ the area, in which the appearance of initial electrons leads to increase in avalanches to the size of their transformation into the streamer has been determined. The results based on the calculations of the electric field and the growth of electron avalanches in the space around the cylindrical electrode, are shown in Fig. 6a as the shaded area. The outer boundary of the area corresponds to the electric field strength $E_i = 26 \cdot 10^5\,\text{В/м}$ of the ionization threshold of molecules in air at atmospheric pressure. Outside the shaded area near the electrode, despite the very high field strength, the parameter $Q < 20$ is insufficient to transform the avalanche into the streamer. In addition, near the tip of the needle there is an area of continuous electron acceleration, where the field strength is $E \geq 450 \cdot 10^5\,\text{V/m}$. According to calculations, this area occupies a
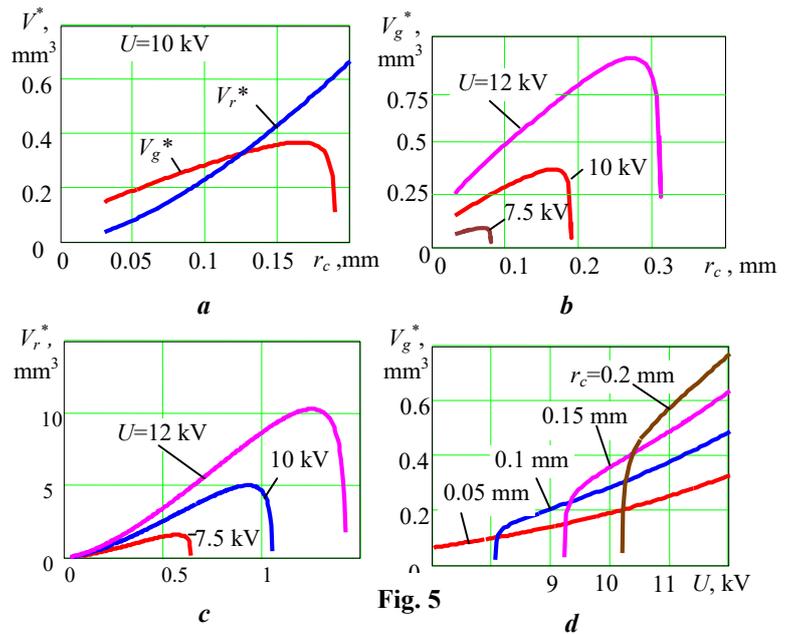

Fig. 5

space with maximum thickness $\approx 0.5 r_c$ near the tip of the needle and, thinning out, extends along the cylindrical surface after tip to a distance $\approx 3 r_c$.

A feature of the start zone of the effective electrons for high-voltage electrode with elongated cylindrical shape is the extension of this zone, which is shaded in Fig. 6, *a*, over a fairly large distance along the electrode. For the data in Fig. 6, the zone thickness gradually becomes thinner and only at length $\approx 0.3d = 100 r_c$ does it sharply decrease to zero. This structure of the zone indicates that the

Fig. 6

above estimates of its volume, which took into account only the area near the needle tip with the highest electric field strength, turn out to be significantly understated for the cylindrical electrode. Experiments performed at the Institute of Electrodynamics with the long cylindrical needle showed that indeed streamers also appear along the cylindrical surface with a characteristic distance between them $\sim 10\ \text{mm}$.

The trajectory of the formed streamer generally coincides with the field line of field. The streamers formed near the side surface of the cylindrical electrode, are developing along the field lines (Fig. 6, *b*), lengths of which are larger compared to those that stats from the peak of electrode. Accordingly, streamers formed at the side surface propagate at lower average field strength. They reach the surface of the opposite electrode if the average field strength along the trajectory of motion exceeds the value $\sim 5 \cdot 10^5\ \text{V/m}$. Otherwise, the streamer stops before reaching the electrode.,

The presented results reflect the areas of the electron avalanche growth only in the external field, when the field of a single avalanche is not disturbed by the charges of previous avalanches and streamers, and possibly by other avalanches or streamer channels propagating nearby. That is, the results relate to the isolated streamers, which is often observed in experiments, and the streamer corona discharge does not have a volumetric character. However, analysis of the field structure of the electrode system with an estimate of the volumes for the appearance of effective electrons can provide certain qualitative indicators even in the case of limited mutual influence of several streamers. The more reliable information about the corona discharge in specific cases can be obtained in the experiment.

Conclusions. The comparison of electrode system configurations intended for the practical application of positive streamer corona was carried out by the volume near the needle, in which the appearance of effective initial electrons leads to the development of avalanches and their transition to the streamer form. This approach allows us to obtain quantitative estimates of the appearance of streamers, which in the complex take into account the configuration of the corona electrodes, the radius of the needle tip and the magnitude of the voltage between the electrodes.

Comparison of the features of the distribution of the sharply inhomogeneous electric field in the electrode systems with the needles of hyperbolic, cylindrical, and spherical configurations showed that, despite the smaller values of the maximum field for the hyperbolic needle, the volume of the appearance of effective initial electrons can exceed the volume near the needle tip for cylindrical and, even more, for spherical electrodes of the same curvature radii. This feature is related to the influence of the shape of the electrode outside its tip to the electric field distribution. The ratio of the volumes of the appearance of effective initial electrons for different needle configurations near the limit values of voltage and the tip curvature radii can vary depending on their magnitudes.

For each value of voltage between the electrodes there is an upper limit of the curvature radius of the tip or, in other words, for each radius of the tip there is a lower limit of the voltage. Moreover, for each value of voltage, the larger the curvature radius of the tip and, accordingly, the lower the maximum electric field strength, the larger the volume of the appearance of effective initial electrons.

A feature of the long cylindrical needle is the spread of the zone of appearance of effective electrons over considerable distance along the lateral surface of the electrode, for example, with tip radius of 0.05 mm, this area has the length of about a hundred tip radii. The thickness of the area along the electrode gradually decreases with distance from the tip and at the end the thickness drops sharply to zero. Streamers can also start from the area near the lateral surface of the electrode, however their lengths are greater than those that
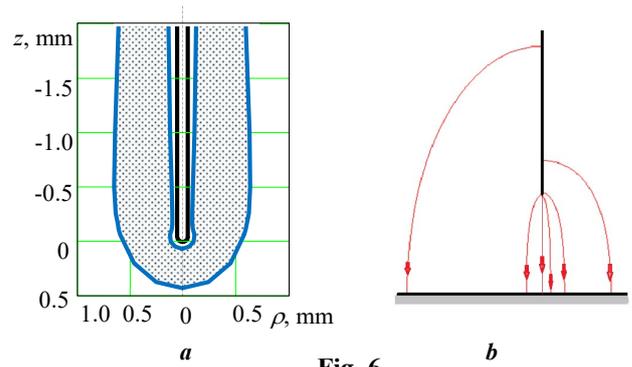
depart from the tip. Such streamers reach the surface of the opposite electrode when the average field strength along the trajectory of movement of the streamers exceeds $\sim 5 \cdot 10^5 \, \text{V/m}$.

For the distance between the electrodes of 15 mm and the voltage up to 15-20 kV, which does not exceed the spark breakdown voltage, with an increase in the curvature radius of the needle tip at least to values of (0.3 - 0.5) mm, the volume of the appearance of effective electrons that generate streamers increases, which indicates the feasibility of choosing the appropriate tip radius for intensification of the streamer process.

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УМОВИ ПОЯВИ ПОЗИТИВНОГО СТРИМЕРНОГО КОРОННОГО РОЗРЯДУ У ПОВІТРІ В ЕЛЕКТРИЧНОМУ ПОЛІ ВІСТРЯ ПРОТИ ПЛОЩИНИ

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*Особливості позитивного стримерного коронного розряду, що характеризуються великою довжиною і часом існування кожного стримерного утворення, визначають його як одного з альтернативних шляхів потенційного технологічного застосування і характеризують актуальність досліджень у цьому напрямі. **Метою** роботи є визначення впливу геометричних характеристик вістря та напруги між електродами на величину областей, початок розвитку лавин електронів з яких призводить до їх перетворення у стримерну форму коронного розряду в повітрі за атмосферного тиску. Для електродних систем з вістрям у формі гіперболоїду і параболоїду обертання, сфери і довгого циліндру розглянуто розподіл електричного поля і визначено об'єм областей, де поява ефективних початкових електронів призводить до їх розмноження до стадії лавинно-стримерного переходу. Встановлено, що на величину вказаних об'ємів окрім радіусів кривини кінцівок суттєвим чином впливає форма електроду поза частиною його поверхні з найменшим радіусом кривини. Показано, що незважаючи на менші значення максимального поля для гіперболічного вістря, величина об'єму появи ефективних початкових електронів може перевищувати величину об'єму для циліндричного і, тим більше, сферичного електродів того ж радіусу кривини кінцівок за однаковому значенні міжелектродної напруги. Особливістю довгого вістря циліндричної форми є розповсюдження зони старту ефективних електронів на значну відстань вздовж бічної поверхні електроду. З порівняння різних електродних систем зроблено висновок, що вибір може виконуватися за величиною об'ємів появи ефективних електронів як кількісного показника, який враховує конфігурацію вістря, радіуси кінцівок і величину напруги. Бібл. 24, рис. 6.*
Ключові слова: позитивна стримерна корона, електричне поле вістря проти площини, лавинно-стримерний перехід, показник ефективності появи стримерів.