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MULTI-NEEDLE ELECTRODE SYSTEM WITH A METAL DISC DESIGNED FOR OZONE PRODUCTION IN THE STREAMER CORONA DISCHARGE

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The search for methods for taking into account a significant number of factors that affect the development of a positive corona discharge in technological processes determines the relevance of research in this area. The aim of the work is to determine for the streamer corona discharge in air at atmospheric pressure the influence of the geometric configuration of a multi-needle electrode system with a metal disk, as well as the air flow rate with its supply along the needles on the distribution of the electric field, the fulfillment of the avalanche-streamer transition condition, the ozone output and the energy consumption required for this. It is shown the existence of threshold values for the interelectrode voltage, needle lengths and distance between the needles, which limit the possibility of the appearance of streamers in the corona discharge. Based on the experimental results, in relation to energy consumption, it can be concluded that there are optimal values for the length of needles and the distance between them. It was found that an increase in air flow in the electrode system during ozone production leads to a decrease in specific energy consumption and simultaneously to a decrease in ozone concentration. This relationship, depending on the purpose of the streamer corona discharge, must be taken into account in its practical application. References 7, figures 4, tables 2.
Key words: positive streamer corona, multi-needle electrode system, ozone output, energy consumption, optimization of the electrode system.

Introduction. At present, the use of corona electric discharge in gas, which occurs in a sharply inhomogeneous electric field, for example, near the needle, does not lose its importance. The attractiveness of this type of electric discharge lies in the efficiency of creating electrically charged and chemically active particles, which is carried out by electrons and photons that arise in the corona discharge. When using a positive streamer corona discharge, the electric field strength near the head of the streamer, which propagates to the cathode at high speed, reaches a significant value [1]. In such field, electrophysical processes occur with intensive generation of ozone, active radicals and other particles. In addition, a streamer discharge can appear in certain operating modes of high-voltage devices [2]. Therefore, its study, along with the study of other types of corona discharge [3-5], appears to be an urgent problem.

In experiments and practical applications of corona discharge with corona-forming needles, an electrode system with a metal disk parallel to another usually grounded electrode is widespread. The metal disk is a platform for a multi-needle electrode, and it also limits the length of the needles. The disk significantly affects the distribution of the electric field, reducing the field strength near the tip and simultaneously increasing its value in the rest of the interelectrode space. Hence, it is importance to study the influence of the presence of the metal disk, the length of the needles and their mutual arrangement on the parameters of the streamer corona discharge and ultimately on the efficiency of the corona discharge in technological application.

The **aim** of the work is to determine for the streamer corona discharge in air at atmospheric pressure the influence of the geometric parameters of multi-needle electrode system with the metal disk, as well as the air flow rate with its supply along the needles on the distribution of the electric field, the fulfillment of the avalanche-streamer transition condition, the ozone output and the energy consumption required for this.

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Geometric parameters of the electrode system and mathematical model. The metal disk and the needles are under the same positive potential $\varphi = U$ opposite the grounded flat electrode. The geometric parameters of the main elements are shown in Fig. 1: $d = 15$ mm is the interelectrode distance, which is constant in this work, h is the length of the needle, a is the distance between the needles, $r_c = 0.05$ mm is the radius of the cylindrical needle, which has a rounded tip of the same radius (in the calculation part).

The calculations use a simplified mathematical model that considers the growth and drift of electron avalanches without taking into account the electric field of the charge of ions distributed in space. This approach is often used in the study of processes with separated avalanches and streamers [1] and allows us to focus on identifying the influence of the main factors affecting the parameters of the corona discharge.

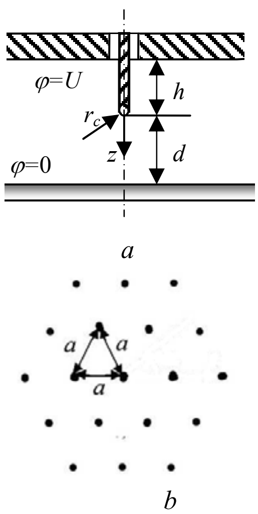

Fig. 1

The increase in the number of electrons N_e in the avalanche was calculated taking into account the effective impact ionization coefficient α_{ef}. The dependence of the coefficient α_{ef} on the strength of the electric field E was determined using the approximation containing the parameters A and B, the values of which are given in [1, 6, 7]

$$N_e(\xi) = \exp\left(\int_{\xi_0}^{\xi} \alpha_{ef}(\xi') d\xi' \right), \text{ де } \frac{\alpha_{ef}}{p} = A \exp\left(-\frac{B}{E/p} \right). \quad (1)$$

Here p is the air pressure; ξ is the coordinate along which the avalanche of electrons moves (usually it is a field line); ξ_0 is the position of the initial electron. For ionization of air molecules, the field strength must exceed the threshold $\approx 26 \cdot 10^5$ V/m.

The avalanche-streamer transition for atmospheric pressure air was determined by reaching a certain number of electrons in the avalanche [1, 6]

$$Q = \ln(N_e) = 20. \quad (2)$$

Calculation of the growth of electron avalanches and fulfillment of the avalanche-streamer transition condition. *In the case of the electrode system with one needle*, at selected values d and r_c the parameters affecting the electric discharge processes are the needle length h and voltage U. In a sharply inhomogeneous field of a thin needle, the beginning of ionization of molecules, where the field strength begins to exceed the ionization threshold, is possible near the needle. The avalanche of electrons, increasing, drifts in the direction to the needle and at a certain distance from it the condition of the avalanche-streamer transition (2) can be met. For different needle lengths h at a voltage $U = 17$ kV, the corresponding values z_i of the distances of the ionization threshold and the appearance of streamers z_Q on the symmetry axis z, as well as the field strength E_Q at the points of transformation of the avalanche into the streamer are given in

Table 1

h, m	z_i, m	z_Q, m	E_Q, V/m
$5 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	$3.0 \cdot 10^{-5}$	$290 \cdot 10^5$
$7 \cdot 10^{-3}$	$4.5 \cdot 10^{-4}$	$4.5 \cdot 10^{-5}$	$260 \cdot 10^5$
$10 \cdot 10^{-3}$	$5.2 \cdot 10^{-4}$	$6.6 \cdot 10^{-5}$	$230 \cdot 10^5$

The table shows that as the needle length increases, the distance at which ionization of molecules is possible increases. This means that the region near the needle tip also increases, the appearance of initial electrons in which leads to the growth of avalanches and their transformation into streamers. The needle length at which the avalanche-streamer transition condition (2) is met has a threshold character. This is explained by the fact that when the electric field strength in the ionization zone decreases for shorter needle, the number of electrons in the avalanche on the maximum path of its growth cannot reach the required values under condition (2). For example, for the voltage $U = 17$ kV, the appearance of streamers is impossible at a needle length of $h < 3$ mm. For each needle length, there is also a lower voltage limit below which the avalanche-streamer transition condition cannot be met (voltage threshold value). As the needle length increases, the threshold voltage value decreases. For example, for $h = 7$ mm the threshold value calculated by the mathematical model is $U \approx 9$ kV, and at $h = 10$ mm such voltage is $U \approx 7$ kV.

In the case of multi-needle electrode, another geometric parameter that affects the development of the electric discharge process is the distance (step) between adjacent needles. For voltage $U = 17$ kV, the dependence of the parameter Q on the distance a is shown in Fig. 2. For the needle lengths $h = 5, 7, 9, 15$ mm, the corresponding curves are sequentially marked with numbers 1, 2, 3, 4. The figure shows that to fulfill the condition $Q = 20$, that is, to induce a streamer discharge in the gap, the step between the needles must exceed the minimum value $a_{\min} = 5$ mm. At the same time, the needle length in the range $h = 5...15$ mm has a weak effect on the value $a_{\min}$.

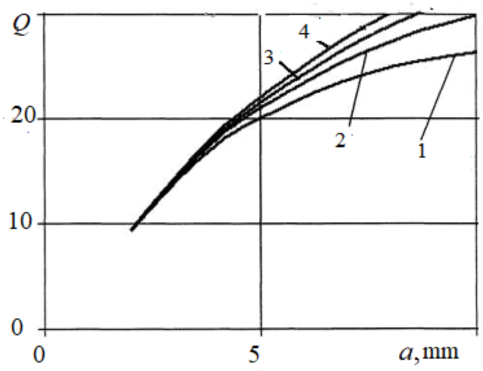

Fig. 2.

Taking into account the results of the calculations, for the experimental study of the efficiency of the streamer corona discharge using a multi-needle electrode, anodes were chosen, in which the distance between needles exceeded 5 mm.

Experimental studies. In contrast to the calculations, the needles in the experiments were platinum-rhodium strips with a cross section of 0.06×0.3 mm. The disk had holes for individual blowing of the needles (shown in Fig. 1 as unshaded areas of the disk near the needle surface). The constant voltage of positive polarity was applied to the electrodes from a stabilized high-voltage power source. Signals for recording currents and voltages were taken, respectively, from a low-inductance shunt and an ohmic voltage divider and fed to the input of electronic devices, the characteristics of which allow recording the features of electric discharge processes. The ozone concentration C was measured optically by the absorption of ultraviolet (UV) radiation in a gas cuvette, to which radiation came from an external source of UV light. The concentration value C was determined based on the Bouguer-Lambert-Beer law $R = R_0 \exp(-mG_\lambda C)$, where R_0 and R are the signal values at the output of the photomultiplier in the absence and presence of ozone in the cuvette, respectively, m is the optical length of the cuvette, G_λ is the cross section of ozone absorption of radiation at the wavelength λ. Measurements were carried out at wavelengths of 254.7 and 275 nm.

Single-needle electrode. The study of the characteristics of the single-needle corona discharge allows for comparison with the corresponding characteristics of the multi-needle electrode system, which can have practical applications. An example of the corresponding characteristics at h = 9 mm, d = 15 mm and air flow rate V = 5 l/min is shown in Fig. 3. From the current-voltage characteristic (I-V) of the discharge (curve 1) it can be seen that the voltage at which corona appears is 7 kV. The time-averaged corona discharge current I in the experiments reaches the highest value I_m = 180 μA at the applied voltage U = 17 kV. At current value I close to 40 μA, an inflection is observed on the I-V characteristic, after which the steepness of the current increases with increasing voltage U. The current at the inflection point of the curve corresponds to the appearance of the measured value of the ozone concentration C (curve 2). With a further increase in the discharge current, the concentration C continuously increases, and the specific energy consumption for ozone generation W decreases (curve 3), which at $I = I_m$ reach values of 0.35 mg/l and 30 kWh/kg, respectively.

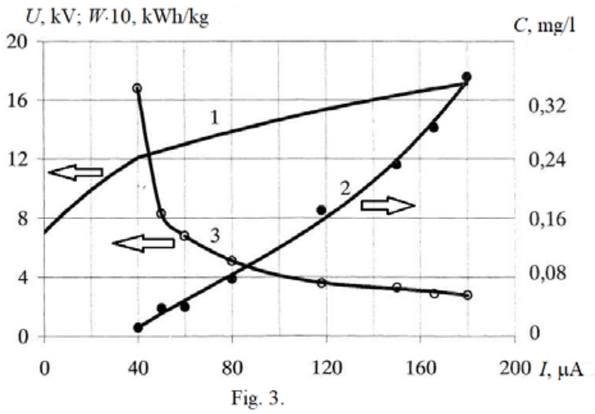

Fig. 3.

The discharge current recording on the oscilloscope shows that near inflection point on the I-V characteristic a short streamer current pulses (200 ... 300 ns) with amplitudes i_m ~ 10 mA appear. With an increase in the averaged discharge current to I = 180 μA, the pulse amplitudes i_m reach values of 70 mA.

Studies have shown that the discharge parameters significantly depend on the gas flow rate. An increase in the gas flow rate at a constant input power leads to a decrease in the ozone concentration and specific energy consumption. For example, at air flow rates V in the range of 0.2...27 l/min, the values of C and W vary, respectively, within the limits of 2.5...0.1 mg/l and 70...20 kWh/kg. Increase in the ozone concentration to maximum values of 2.5 mg/l is observed with a simultaneous decrease in the streamer current amplitude to 20 mA. This indicates a significant influence of negative ozone ions O_3^- with a high electron affinity energy (2.1 eV [1]), which is associated with a decrease in the concentration of electrons, which primarily provide electrical conductivity of the plasma of the streamer channels.

The presence of the metal disk in the electrode system contributes to an increase in ozone yield with a decrease in specific energy consumption. For example, with a needle length of h = 9 mm, the specific energy consumption is reduced by more than half compared to the absence of such disk. This can be seen from Table 2, which shows the results obtained under the same conditions in the absence and presence of the metal disk, lines 1 and 2. The increase in energy consumption in the absence of the metal disk can be associated with a large proportion of the electron avalanche current along the lateral surface of the long needles not limited by the disk.

Multi-needle electrode. Experiments performed with different needle lengths h and distances between them a allowed us to establish the optimal geometric dimensions in terms of the specific energy consumption for ozone generation W. The corresponding values are given in row 3 of Table 2. A comparison with a single-needle electrode in row 2 shows that the distance between the needles has a smaller effect than the needle length (at least at the distances between the needles that are not less than their length).

Table 2

Number of needles	h, mm	a, mm	V, l/min	W, kWh/kg
1	∞	-	7	68
1	9	-	7	30
14	9	10	7	29
36	4	7	7	46

Changing the main geometric dimensions of the electrode system (h and a) to values that go beyond the optimal ones leads to an increase in specific energy consumption. This is evident from the data in row 4 of the table, in which at h = 4 mm and a = 7 mm the value W = 46 kWh/kg is one and a half times higher than W at the optimal h in row 3.

The characteristics of the multi-needle electrode at the optimal values of the geometric parameters h = 9 mm and a = 10 mm are presented in Fig. 4. Curve 1 shows that the ozone concentration decreases from 2 mg/l at low air flow rates V = 1 l/min to 0.4 mg/l with increase in the flow rate to 12 l/min. The maximum concentration of C = 3 mg/l was obtained at minimum flow rate V = 0.2 l/min (not shown in Fig. 4). The specific energy consumption W for ozone production, as for a single needle, decreases with increase in the value of V (curve 2). At the air flow rate V = 11 l/min, they are 20 kWh/kg. A further increase in V to 25 l/min leads to a decrease in the energy consumption W to 14 kWh/kg. Note that this value is characteristic of a barrier discharge in undrained, as in our case, atmospheric air.

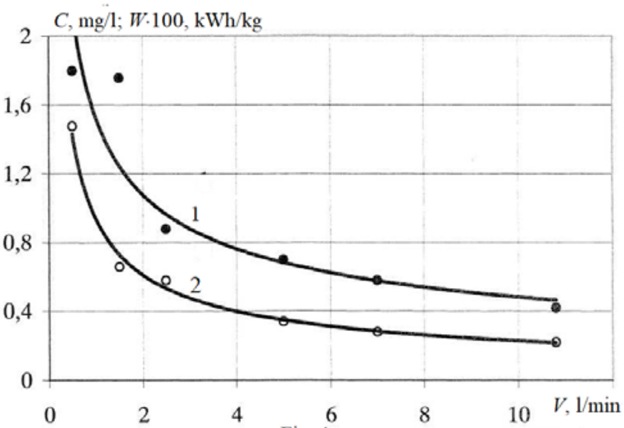

Fig. 4.

Conclusions. Computational studies on the fulfillment of the condition of the avalanche-streamer transition in the electrode system of the needle, the length of which is limited by the metal disk, against the plane showed the existence of threshold values of the needle length and the constant interelectrode voltage, below which the appearance of streamers is impossible. In the multi-needle electrode, for the appearance of streamers, the distance between the nearest needles must also exceed the certain threshold value.

Experimental studies of ozone generation in the multi-needle electrode system and the energy consumption required for this have shown the existence of optimal energy consumption values for the needle length and the distance between them. It turned out that the needle length has the main influence, while for systems with different distances between the needles exceeding a certain value, the specific energy consumption for ozone generation differs little.

Experiments show that in streamer corona discharge, the air flow rate during ozone production has a different effect on the ozone concentration in the air and the energy consumption required for this. With an increase in the air flow rate (from 2 to 12 l/min), on the one hand, the ozone concentration, which is desirable to have larger, decreases significantly (from 2 to 0.4 mg/l), on the other hand, the specific energy consumption decreases (from 60 to 20 kWh/kg). Therefore, there is probably an optimal air flow rate, which may differ depending on the purpose.

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БАГАТОГОЛЬЧАСТА ЕЛЕКТРОДНА СИСТЕМА З МЕТАЛЕВИМ ДИСКОМ, ЩО ПРИЗНАЧЕНА ДЛЯ ВИРОБЛЕННЯ ОЗОНУ У СТРИМЕРНОМУ КОРОННОМУ РОЗРЯДІ

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Пошук методів врахування значної кількості факторів, що впливають на розвиток позитивного коронного розряду у технологічних процесах, визначає актуальність дослідження у цьому напрямку. Метою роботи є визначення у стримерному коронному розряді в повітрі атмосферного тиску впливу геометричної конфігурації багатогольчатої електродної системи з металевим диском, а також розходу повітря з його подачею вздовж вістря на розподіл електричного поля, виконання умови лавинно-стримерного переходу, вихід озону та необхідні для цього енерговитрати. Показано існування порогових значень міжелектродної напруги, довжини вістря та відстані між вістрями, які обмежують можливість появи стримерів у коронному розряді. На основі експериментальних результатів стосовно споживання енергії зроблено висновок про можливість існування оптимальних значені довжини голок та відстані між ними. Виявлено, що збільшення витрат повітря в електродній системі при вироблені озону призводить до зменшення питомих витрат енергії та одночасно до зменшення концентрації озону. Такий зв'язок в залежності від призначення стримерного коронного розряду необхідно враховувати при його практичному застосуванні. Бібл. 7, рис. 4, табл. 2.
Ключові слова: позитивна стримерна корона, багатогольчаста електродна система, вихід озону, енерговитрати. оптимізація електродної системи.

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