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The Physical Experimental Modelling of the Formation Processes of Upward Discharges from Grounded Objects in the Artificial Thunderstorm Cell's Electric Field

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Abstract: The results of the physical modelling of the formation processes of upward discharges from grounded objects in the artificial thunderstorm cell's electric field are presented. We established the considerable influence of the electrode tip's radius on the pulse streamer corona stem's parameters and, subsequently, on the probability of the transformation of the impulse streamer corona first flash's stem into a first stage of upward leader. We determined the diapason of the optimal tip radii for a lightning rod or lightning conductor, which allows for the most probable formation of the first impulse streamer corona, with the parameters providing the best conditions for the upward leader's start, the purpose of which is the lowering of the probability of lightning striking the object under protection. A considerable difference between the electrical characteristics of the first impulse corona flash with and without the streamer–leader transition was established. It was shown that the amplitude of the streamer corona flash current impulse is considerable, but not the main defining factor of the streamer–leader transition. It is established that the charge value of the streamer corona first flash is not a threshold requirement for the formation of the upward leader from a ground object, but only defines the probability of the successful upward leader formation. Based on the analysis of the experimental data received, we suggest that there is a dependency between the probability of upward positive leader formation from the grounded objects and the charge value of the first pulse streamer corona flash for the rod (centered) and rope (elongated) lightning conductors and objects in the electric field of the thundercloud and downward lightning leader. The obtained results can be used for mathematical modelling of the formation processes of upward discharges from grounded objects in the artificial thunderstorm's electric field, as in a natural thunderstorm situation.

Keywords: lightning; upward discharges; artificial thunderstorm cell; physical simulation; first impulse streamer corona flash; stem; streamer–leader transition; model lightning rod and lightning conductor; probabilistic criterium

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1. Introduction

Despite the obvious successes in solving lightning protection problems and researching lightning physics, presently we are still facing some considerable and relevant fundamental and practical problems in the physics of lightning formation, lightning striking grounded objects, and ensuring their reliable lightning protection [1–5]. The reason for this is the increasing technical functionality and complexity of the grounded objects, which, in turn, leads to increased requirements for their lightning protection systems.

More specifically, the research is focused on the formation processes of upward discharges from grounded objects and lightning rods (conductors), which generally determine the probability of lightning striking a grounded object and the efficacy of its lightning protection, as well as how the regulatory documents and calculation methods used in the lightning protection industry can be perfected [1,2,4–9]. Modelling of upward leader formation processes is based on the various experiments taking place within long air gaps, which, in one way or another, model thunderstorm conditions, and use considerably different criteria for upward positive leader formation [2,4,6,7,10–14], including questions of streamer–leader transition [11,15–18].

The exact formation processes of the upward (counterpart) leader in the thundercloud's electric field and of the downward stepped leader from lightning rod/conductor and/or protected object are not yet fully known [2,6,7,10,12,13,16–23]. The stage preceding leader formation—the stage of creation and development of the impulse corona stem, its transition into the first leader stage, and the subsequent development located between the two main stages of discharge formation in the air (streamer and leader stages) is presently the least studied one. Nevertheless, it is a key stage in determining the conditions of the earlier transition in the first streamer flash (practically without a dark period) from the lightning diverter into an upward leader and its more advanced development in comparison with analogous discharge processes on the protected object. The leader which appears first on one of the grounded electrodes weakens the electrical field under it with the volume charge of its cover and complicates the formation and development of opposite discharges from other adjacent electrodes [2,24–26].

Today, there are a few different approaches to the modelling of the processes of upward leader initiation, defined either by a certain threshold value or a formula for its definition as a criterion of the upward positive leader's formation [2,11,27]. They are based on experiments, as well as physical and mathematical modelling performed with consideration of laboratory experimental results and observations of natural and trigger lightning. The following are used as criteria for the upward positive leader's formation [2,21]:

- critical length of the streamer zone (from 0.7 m to 2.2 m);
- critical intensity of the electric field created by a thundercloud and downward lightning leader at a certain distance from the tip of the grounded object (from 400 kV/m to 500 kV/m);
- critical potential induced at the point of the grounded object's tip (without the object itself), from 700 kV to 1600 kV;
- critical intensity of the electric field created by a thundercloud and downward lightning leader at the point of the grounded object's tip (it is supposed that its value depends on the object's height);
- critical volume charge of the streamer corona forming from the grounded object (~1 microcoulomb).

Although the conditions of upward leader formation and development were being researched for decades, which physical mechanisms prevail during the formation, development, and transition to the leader stem pulse corona section is not universally agreed upon, especially for the first streamer corona flash. The science lacks experimental data regarding the conditions of the stem formation and its transition into leader section, which could specify the physical mechanism models in the pulse corona stem, which provide for its successful transition into an upward positive leader within an electric field of a downward leader and a thundercloud. Moreover, it is still not clear how lightning conductor's and protected object's parameters (form, tip curvature radius, size) influence the transition process [6,10,19,22,28].

Hence, one of the key areas of modern lightning protection is to study the mechanisms of upward leader formation as a stage of striking ground objects by negative lightning, to identify the influence of parameters of lightning rods/conductors and protected objects on the processes of initiation of upward (intercepting) leaders from them under exposure of the electric field of a thundercloud and the downward stepped lightning leader.

Using experimental methods to study and solve the problems of the physics of lightning and lightning protection of ground objects was, and still is, important for the physical and mathematical modeling of lightning discharge formation and lightning striking lightning rods and protected objects, as well as for testing and the detailed analysis of the possible effectiveness of existing and potential lightning protection methods and means [14,29–34]. In addition to the use of pulse voltage generators, one of the directions in the physical modeling of lightning discharge damage of objects may be the use of artificial thunderstorm cells of negative polarity with a potential of more than 1 MV, which brings the physical modeling of the lightning damage process of ground objects significantly closer to the natural lightning conditions and allows for the formation of a statistically significant data bank [33,35].

The article presents the following data:

- a generalization of experimental studies (physical modeling) of the processes of first impulse streamer corona stem formation in the electric field of an artificial thunderstorm cell of negative polarity,
- revealed key physical mechanisms during the formation and development of the first impulse streamer corona stem, and its transition into the first section of the ascending leader, and
- the criterion for the emergence of the upward positive leader from lightning diverters and grounded objects in the electric field of a thundercloud and downward lightning leader.

The obtained results will allow not only for the clarification or modification of the methods of calculation of protection of ground objects from direct lightning strikes, but also for determining the ways to further improve the lightning protection of ground objects by ensuring the priority initiation of the rising leader from the lightning rod immediately after the primary impulse streamer corona flash.

2. Physical Modeling of the Processes of Occurrence of Upward Discharges from Ground Objects in the Electric Field of an Artificial Thunderstorm Cell

Physical simulation of the processes of the occurrence of upward discharges of ground objects in the electric field of an artificial thunderstorm cell of negative polarity was performed at the experimental complex "GROZA", which allows the creation of artificial thunderstorm cells (artificial thunderclouds) with a potential of up to 1.5 MV. The characteristics of the experimental complex and the artificial thunderstorm cells created by it are presented in [33,36–38]. The basic scheme of the experimental measuring complex is shown in Figure 1.

When physically modeling the processes of an upward leader as a stage in the lightning strike of ground objects, the charging device of the charged aerosol generator provided the discharge current of 100–120 μA. The main part of the artificial thunderstorm cell was formed at distances from 0.5 m from the nozzle device with a lower boundary at a height of 1.0 m above the grounded electrostatic screen. The length of the main part of the cell was 3.0 m. The transverse dimensions of the main part of the cell were, on average, 0.8 m, varying from 0.45 m in the near-nozzle area to 1.2 m at a distance of 3.5 m from the nozzle. As a result, a strong electric field with a maximum intensity up to 8 kV/cm near the grounded plane and up to 18 kV/cm near the boundaries of the artificial thunderstorm cell was created in the interval "artificial thunderstorm cell—grounded plane". At the same time, during the operating mode of the experimental installation in the area between the lower boundary of the artificial thunderstorm cell being created and the grounded horizontal plane at heights up to 0.5 m above the grounded plane at a distance of 1.0 to 2.4 m from the nozzle of the charged aerosol generator, the electric field has an almost quasi-homogeneous character. The value of the electric field strength changes relatively slowly with height (it grows by no more than 30–40%, from 8 to 10 kV/cm at the plane itself, to 11–13.5 kV/cm at a height of 0.5 m above it). The formation of the upward discharge occurred in a slowly growing electric field (the maximum intensity values were reached in one second [39,40]). A model concentrated (rod) or elongated (cylindrical) object up to 0.45 m high was in the region of an almost quasi-uniform field.

The radius of the spherical (conical at the small radii of the curvature tip) tip of the model rod electrode varied within the range from 0.05 cm to 3.5 cm. The main experimental series were performed for the tip radii of the model rod electrode of 0.9 cm, 1.5 cm, 2.0 cm, and 2.5 cm, respectively. The height of the rod electrode ranged from 16 cm to 47 cm. The radius of the elongated (cylindrical) electrode varied from 0.15 cm to 3.0 cm. The main experimental series were conducted for the radii of model wires and cables 0.55 cm, 0.9 cm, 1.5 cm, and 1.75 cm, respectively. The height of the extended electrode location ranged from 15 cm to 37 cm. To reduce the influence of bias currents on the electrical characteristics of the discharge phenomena formed from the top of the grounded model object, the top of the rod electrode was electrically isolated from the main rod part. For the same purpose, the central part of the extended model electrode a few centimeters in size was insulated from the rest of the metal tube, which was connected to the grounding device.

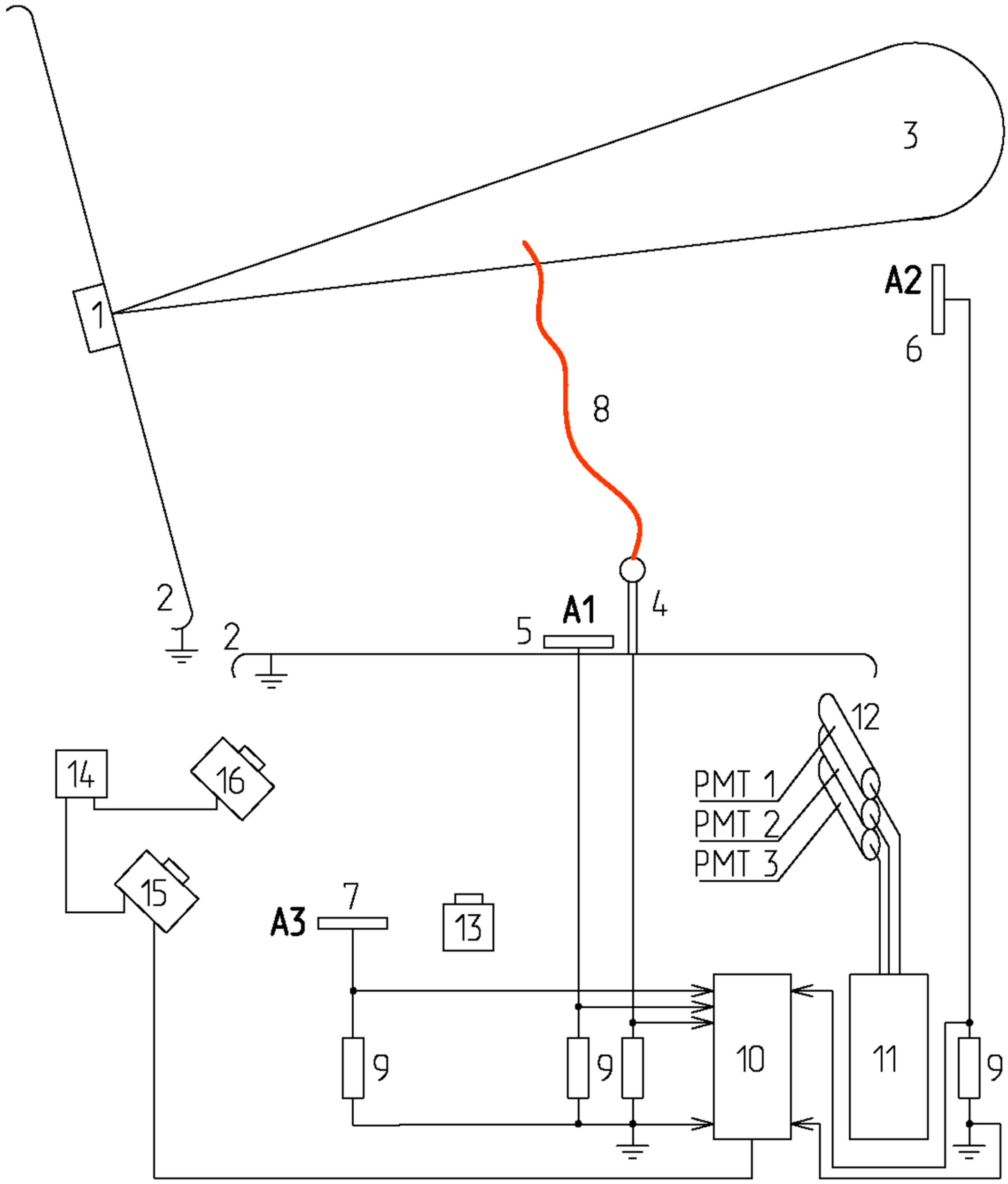
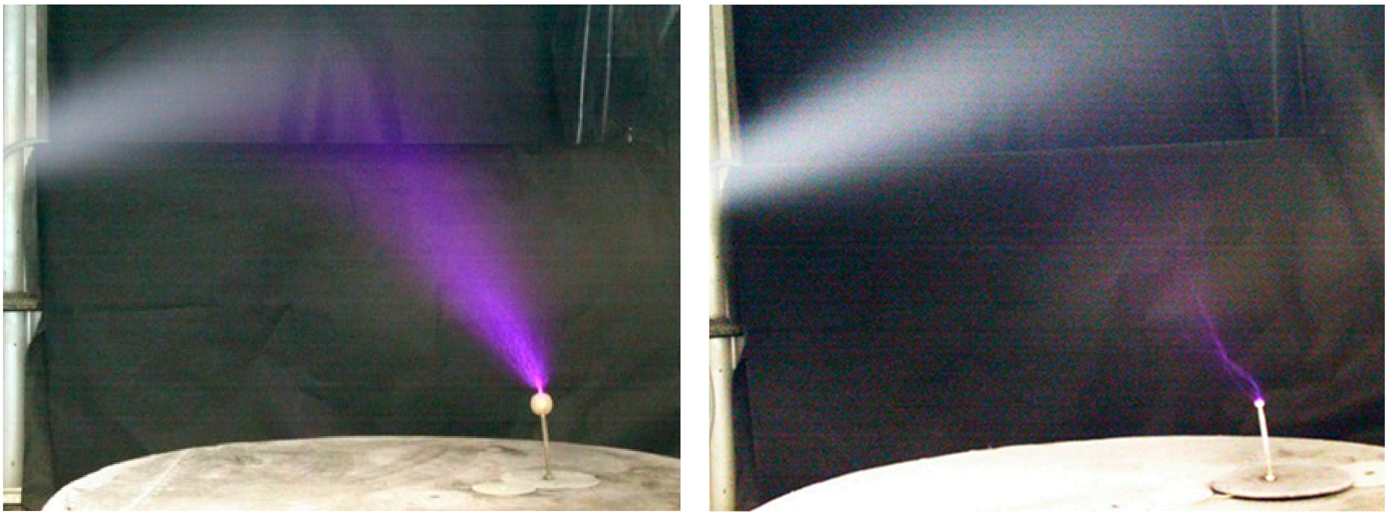


Figure 1. Basic scheme of the experimental measurement complex: 1—charged aerosol generator, 2—grounded electrostatic screens, 3—artificial thunderstorm cell, 4—rod or elongated model electrodes, 5–7—flat antennas, 8—spark discharges, 9—low inductive shunts, 10, 11—digital memory oscillographs, 12—a system of photoelectronic multipliers, 13—digital camera, 14—trigger generator, 15—photoelectron multiplier, 16—electron-optical camera.

During experimental studies of the conditions of the formation of the first pulse streamer corona stem and its transition to the first leader stage, both the entire discharge gap and the region of space near the tip of the rod electrode where the pulse streamer corona stem was formed were observed. The optical and electrical characteristics of the pulse corona stem and the cases of its transition to an upward leader were recorded.

In the general case, the streamer flash current pulse and the signals induced by it on the antennas were recorded with Tektronix DPO7254 or Tektronix TDS3054C digital oscilloscopes (Tektronix, Inc., Beaverton, OR, USA). Optical registration of the formation of the pulse streamer corona flash and its transition (or absence of transition) to the upward leader in the gap "artificial thundercloud cell—model of grounded rod or extended electrode on the plane" was performed with a Panasonic Lumix DMC-FZ50 digital camera. The dynamics of the formation of a pulse streamer corona and an upward leader were recorded by an electron-optical camera K011 (BIFO Company, Moscow, Russia) and/or a system of photoelectronic multipliers aimed at different parts of the spacing in question.

Characteristic photographs of the first pulse streamer corona flash, oscillograms of the first streamer corona flash current, and images of the electron-optical camera for the cases with/without an upward leader transition are shown in Figures 2–4.

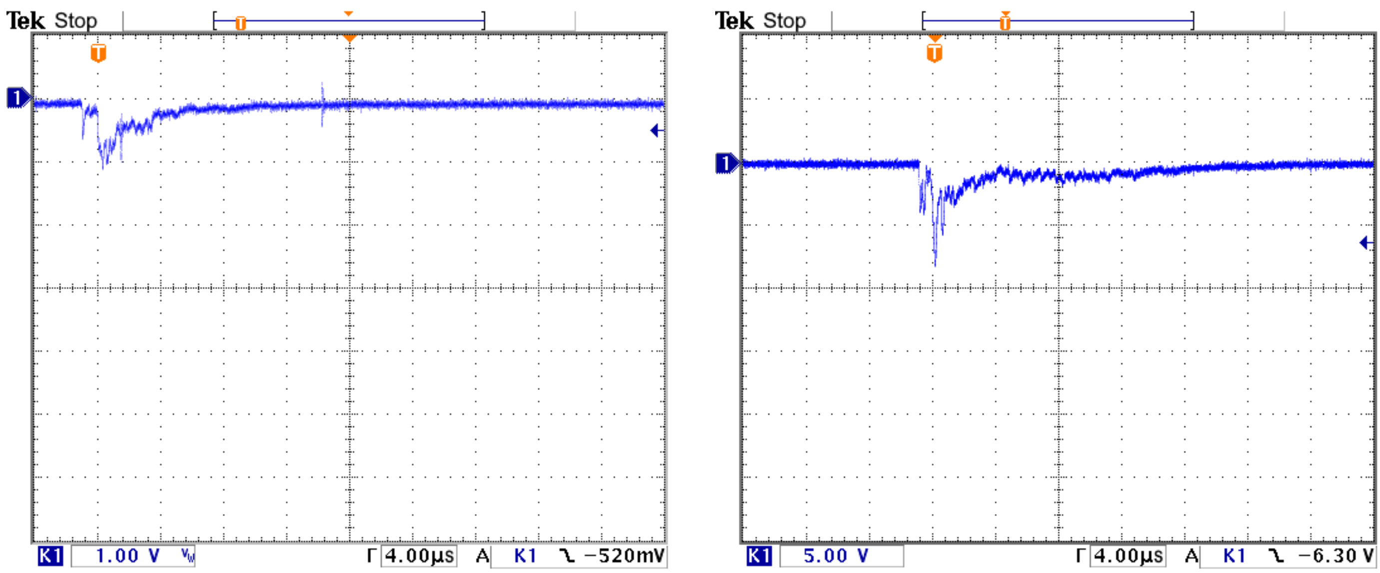


(**a**) (**b**)

Figure 2. Pulse streamer corona flash (**a**) without upward leader transition and (**b**) transitioning into an upward leader.

Analysis of the resulting bank of experimental data show that out of a total of more than 1800 experimental attempts, the first pulsed corona flash transitioned to an upward positive leader in about 67% of cases.

Since the streamer–leader transition during the formation of upward (counterpart) discharges from ground objects and lightning conductors in the thundercloud's electric field and/or a downward lightning leader is usually observed under competitive conditions, it is important to know from which ground element the upward leader will form earlier. The leader, who appeared first on one of the grounded electrodes, weakens the electric field under him with the volume charge of his cover and hinders the occurrence and development of counter discharges from other neighboring electrodes [2,16,25]. It is believed [16] that the time of the emergence of the leader coincides with the time of the emergence of the secondary corona. With electrodes with a relatively small tip curvature, the secondary corona does not occur immediately after or during the primary corona, but after a relatively long dark period, which can leave tens of microseconds. In a competitive situation, the appearance of a secondary corona from the tip of the electrode, leading to the initiation of an upward leader, with a minimal dark pause, or even better, already during the primary corona, will significantly increase the chances of such an ascending leader to intercept the downward lightning leader. Therefore, the probability of a successful streamer–leader transition is considered primarily for the conditions when the first flash of a pulse streamer corona actually “prepared” in the stem the conditions for the emergence of the upward leader without a pronounced dark pause (secondary (leader) corona flashes are induced from the surface of the formed stem already).

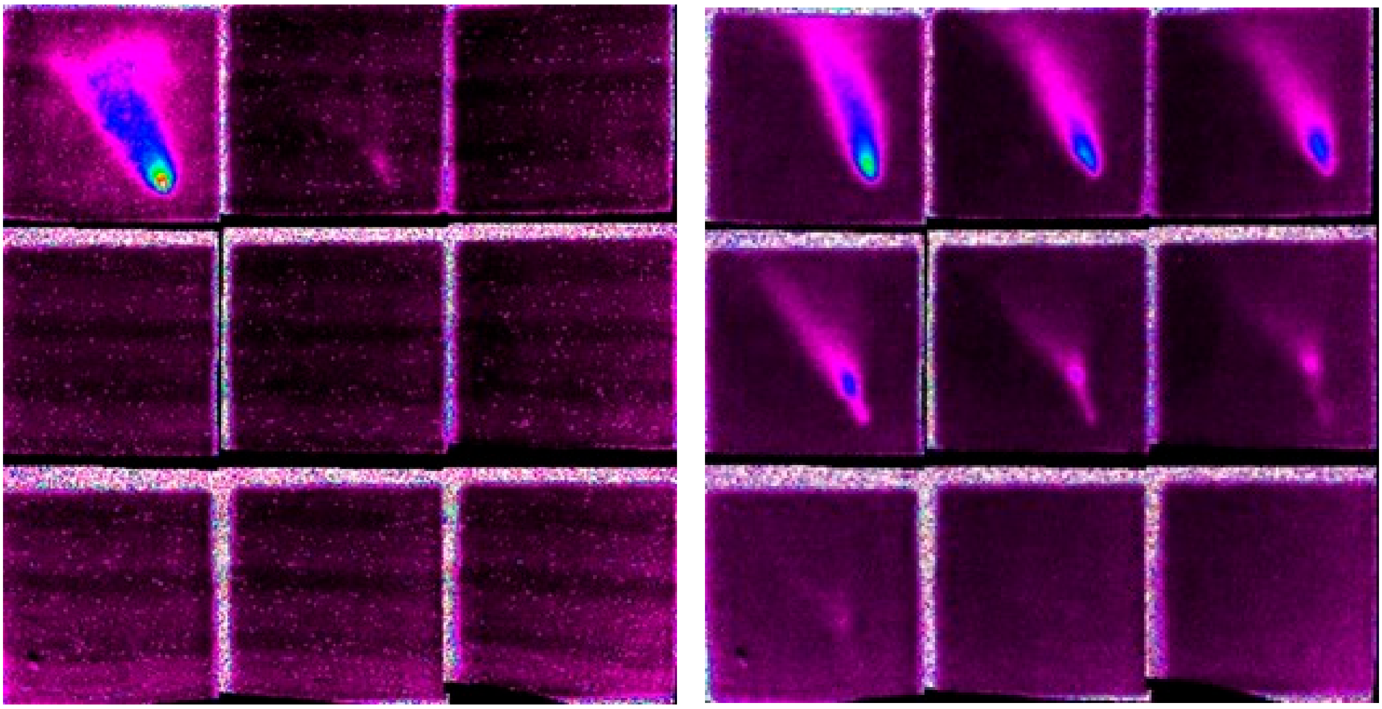


(**a**) (**b**)

Figure 3. Oscillogram of the streamer corona current flowing through (**a**) the stem without transition into the upward leader (shunt 1.39 Ohm, 1 V/del, 4 µs/div) and (**b**) the stem with transition into the upward leader (shunt 1.39 Ohm, 5 V/del, 4 µs/div).

In experiments using a negatively charged artificial thunderstorm cell for the entire range of the curvature radii of the rod electrode’s tip and the diameter of the extended tubular electrode, it was observed that if no upward leader appeared after the first flash of a powerful streamer corona, the next pulse corona flash followed after several tens or hundreds of milliseconds, when processes occurring at the electrode’s tip during the first corona no longer had any significant effect on the formation of the next discharge. This is due to the slow growth of the charged cloud’s electric field and the presence of a feedback between the occurring discharge phenomena and the charge of the artificial thunderstorm cell.

Analysis of the experimental data show that, in the case of using an artificial thunderstorm cell as a source of an external electric field, the flash of a pulse streamer corona from the top of an electrode with a very small curvature radius practically does not lead to the transition of this flash to the first section of the upward leader. On the electrodes with tip radii of less than 3 mm, the power of the streamer flash turned out to be insufficient for the pulse corona stem to develop intensively and have any significant chance of passing to the first section of the ascending leader. In this case, it is common to have the short duration of the streamer flash and its small charge. This is due to the fact that in the slowly growing field of the forming artificial thunderstorm cell, the streamer corona on an electrode with a small top curvature radius appears early, at relatively low field strengths, and is quickly locked by the flash’s volume charge. At the same time, on grounded electrodes with large tip curvature radii (modeled rod objects), even powerful first flashes of a pulse streamer corona do not always lead to a successful transition of this streamer flare to the first section of the upward leader. This is due to the influence of the volume charge of the corona flare on the electric field at the location of the pulse corona stem. As a result, the total electric field at the location of the electrode tip may decrease, and the conditions for the transition of the stem to the first stage of the leader may become worse.



(**a**) (**b**)

Figure 4. Streamer corona flash (**a**) without upward leader transition (frame duration 3.5 µs, pause between frames 0.1 µs, frame size 0.75 × 0.75 m) and (**b**) with upward leader transition (frame duration 2.5 µs, pause between frames 0.1 µs, frame size 0.75 × 0.75 m).

It was determined that the range of the tip radii of the rod electrode from 15 mm to 30 mm (Figure 5) is most conductive for the formation of a pulsed streamer corona with parameters that provide the best conditions for starting the upward leader. For electrodes with larger tip curvature radii, powerful flashes of the streamer corona are more characteristic, at which the probability of transition to the leader decreases. A similar trend was revealed in experimental studies using extended electrode models (models of lightning protection cables or phase wires). The optimum radii of cylindrical conductors (wires), at which the best conditions for leader starting are provided, turned out to be within the range of 0.7 cm to 1.75 cm (Figure 5).

A significant difference in the electrical characteristics of the first flash of a pulsed corona during its upward leader transition and in the absence of a streamer–leader transition was established.

As can be seen in Figure 5, both variants of the grounded electrode models have their own optimal size ranges, at which the probability of the transition of the streamer corona flash to the upward leader reaches the highest values.

As noted in [16], during the formation of the first flash of the streamer corona, two processes have the main influence ("struggle") on the probability of its transition to an upward leader. The first is a complex of electro-gas dynamic processes in the stem of the pulse corona, which can lead to the fact that a secondary corona flare can arise from it and a leader can be initiated. Their intensity is related to the current of the first flash streamers flowing through the stem, whose magnitude is largely determined by the magnitude of the electric field strength on the surface of the electrode and in the space near it. The second is the reduction (shielding) in the electric field strength near the electrode due to the action of the volume charge of the streamer flash, which, in turn, also depends on the magnitude of the external electric field strength. Thus, it can be assumed that at optimal ranges of radii of grounded electrodes, there will be a high probability that a streamer flash from them will ensure the passage of more intense electro-gas dynamic processes inside the pulse corona stem compared to the locking action of the flash volume charge.

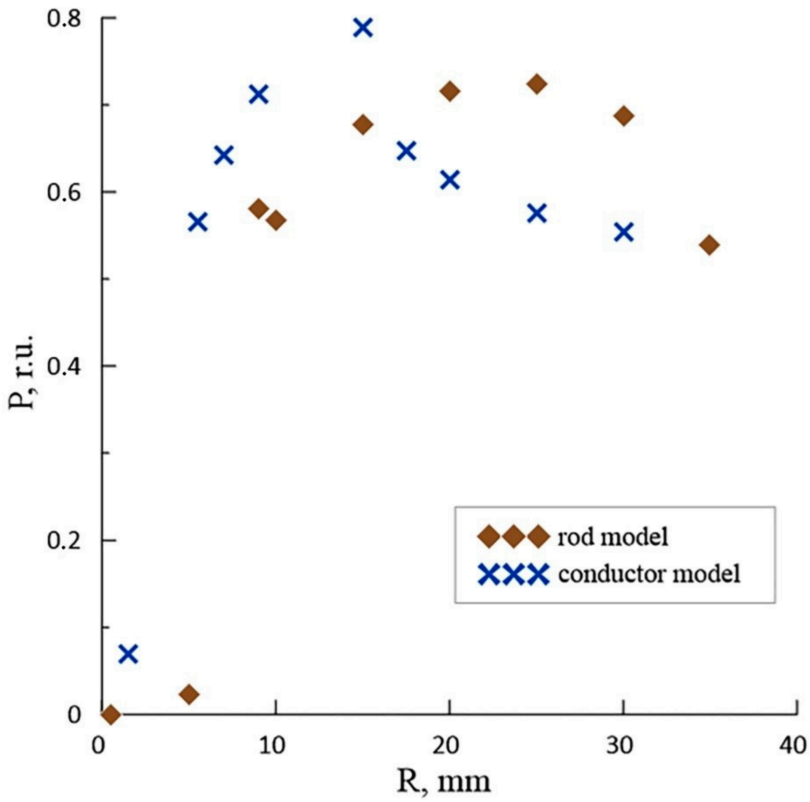


Figure 5. Probability of transition of a pulse streamer corona flash into an upward leader as a function of the tip radius of the rod electrode (radius of the tubular electrode).

It should be noted that this is due not only to the magnitude, but also to the nature of the distribution of the electric field strength near the grounded electrode (accordingly, the shape of the electrode also has a certain effect on the probability of transition to an ascending leader). Firstly, near the cylindrical electrode, the magnitude of the electric field decreases more slowly than near the rod electrode. Secondly, streamer flashes will differ in the shape of the volume of space they will occupy: with a rod electrode, due to the nature of the distribution of the electric field, this volume shape will be closer to a conical one, while with a cylindrical electrode, it will "flatten". Moreover, the larger the radius of the cylindrical conductor, the more this effect will occur. All this leads to the fact that for cylindrical electrodes, the ranges of their radii are optimal for ensuring an upward leader will have smaller values than rod electrodes.

A summary of the results of processing the oscillograms of the first pulse streamer corona flash current obtained in the experiments for different values of the model rod electrode spherical top radius or model cylindrical electrode radius (current pulse amplitude Imax, streamer corona flash duration T_c, streamer corona charge Q_{cor}, streamer corona flash duration $T_{0.5}$ when the current was at the level of more than half of its amplitude value I_{max}), which did or did not transition into the upward leader, are given in Tables 1 and 2 (mean values and scatter (standard deviation)), respectively.

For most parameters of the flash of a pulse streamer corona formed from model rod or elongated electrodes that do not transition to an upward leader, a larger scattering is observed than for the cases in which the streamer flash transitions to an upward leader. For rod electrodes with large tip curvature radii, the duration of a streamer corona flash that transitions into a leader is virtually independent of the size of the rod electrode tip and averages 3–4 µs (which is 1.5 times shorter than the duration of a streamer corona flash that does not result in a leader). It is possible that a longer (slower) formation of the streamer flash causes the total electric field at the location of the electrode tip to decrease, and the conditions for the transition of the stem to the first leader site may worsen.

Table 1. Characteristics of the first pulsed streamer corona flash for experiments with elements simulating the tops of rod objects of a different equivalent radius.

Groups	T_c, ns	I_{max}, A	Q_{cor}, nC	$T_{0.5}$, ns
Without upward leader transition	4917 ± 4574	2.02 ± 1.93	2208 ± 2120	596 ± 581
With upward leader transition	3830 ± 2958	3.04 ± 2.14	2735 ± 2184	995 ± 738

Table 2. Characteristics of the first pulsed streamer corona flash for experiments with elements simulating extended tubular objects of various radii.

Groups	T_c, ns	I_{max}, A	Q_{cor}, nC	$T_{0.5}$, ns
Without upward leader transition	4154 ± 3857	2.54 ± 2.37	3018 ± 2776	674 ± 644
With upward leader transition	3682 ± 2370	3.34 ± 2.29	3650 ± 2453	1227 ± 758

In addition, streamer corona flashes transitioning to the upward leader discharge are characterized by somewhat larger values of the current amplitude and flowing charge. Processing of the experimental data show that the amplitude of the corona flash current pulse I_{max} is significant, but not the main determinant of the transition of a pulse streamer corona flare to an upward leader in comparison with the value of the first streamer flash charge. This result correlates with the data obtained earlier in experiments under similar conditions [33,35].

It was established that the value of the first streamer flash charge is not strictly a threshold criterion for the emergence of the upward leader from a ground-based object, and only determines a possible probability of the successful emergence of the upward leader depending on the value of the first streamer flash charge. It was found that in the conditions of a slowly growing field of an artificial thunderstorm cell, the determining factor in the possibility of the transition of the first pulse corona stem into the upward leader is not only the total pulse corona flash charge flowing through the stem, but also the duration of the time interval $T_{0.5}$, during which the first corona flash current was at a level close to the maximum (Table 3). Apparently, in this case, the energy release at a relatively high level at the base of the streamer corona in the stem continues longer, and the heating of the stem channel and the accompanying gas dynamic processes are more intense.

Table 3. The relative frequency of the duration of the period $T_{0.5}$ when a current of more than 50% of the maximum value flows through the stem, r.u.

Duration Period, µs	0.4 ÷ 0.8	0.8 ÷ 1.2	1.2 ÷ 1.6	1.6 ÷ 2.0	2.0 ÷ 2.4	2.4 ÷ 2.8	2.8 ÷ 3.2
Without upward leader transition	0.29	0.27	0.22	0.14	0.06	0.02	0.0
With upward leader transition	0.01	0.08	0.23	0.29	0.20	0.11	0.08

An essential factor influencing the possibility of the transition of a streamer corona flash to an upward leader is the charge Q_{cor} flowing through its base. It is usually assumed [41] that the transition of the pulse corona stem into the leader region without a dark pause occurs if the radius of the tip of the electrode was at least 3 cm. The first flash charge of the pulse streamer corona, which ensures the transformation of the stem into a spark channel without a dark pause, is estimated to be several µC (from 0.4 µC to 10.5 µC depending on the electrode system and the shape of the applied voltage pulse). However, in experiments using an artificial thundercloud cell, such a transition was also observed at smaller sizes of the corona electrode (up to 1 cm). The experiments showed that the threshold value of the corona pulse charge used in many models of leader emergence really refers to the most preferable range of corona flash charges of 0.8÷1.2 μC for leader emergence (Figure 6).

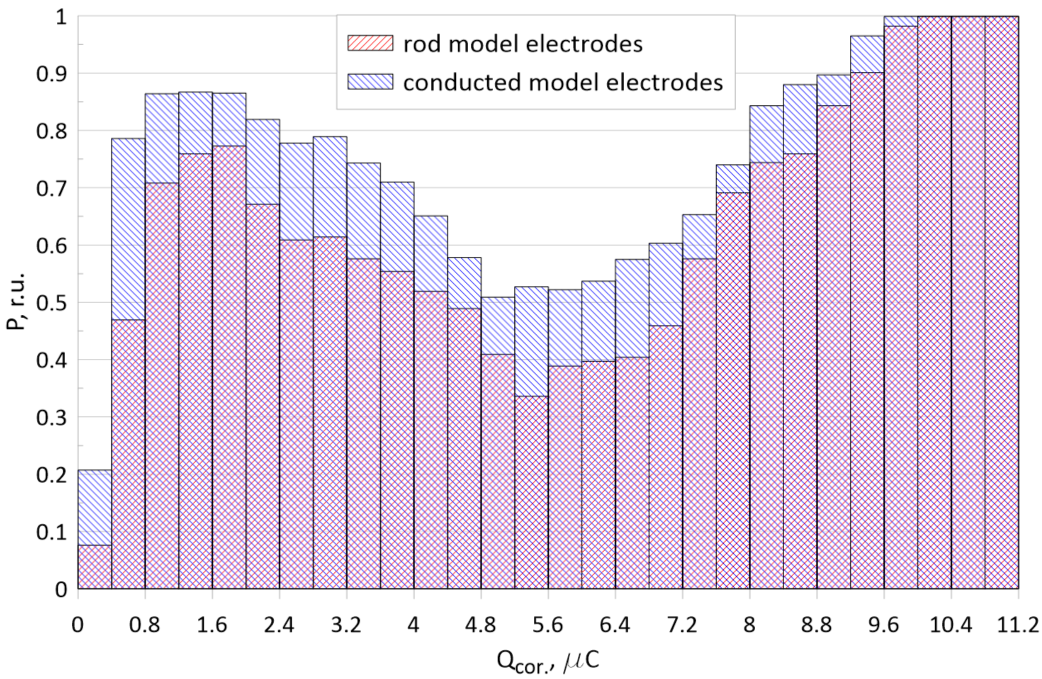


Figure 6. Dependence of the probability of a successful streamer–leader transition (P) on the magnitude of the charge flowing through the base of a pulsed streamer corona flash Q_{cor} (1—rod model electrodes; 2—elongated model electrodes).

In Figure 6, the probability of a successful transition from the streamer to the leader shows a non-monotonic change with the amount of charge flowing through the base of the pulsed flash of the streamer's corona. An increased probability of the transition of a streamer flash to an ascending leader is observed at its charges in the range of ~0.8–2.4 μC. Then, in the range of values of charges of the pulsed streamer corona ~4.4–7.2 μC, the minimum probability of such a transition is observed. With a further increase in the magnitude of the charge of the streamer flash, there is again an increase in the probability of a successful transition of the first flash of the streamer corona to the ascending leader. As noted earlier, such nonmonotonicity may be associated with the prevalence of one of two factors that determine the success of initiating an ascending leader after an outbreak of the primary streamer corona [16]. When charges of several μC are flowing through the stem, intensive electro-gas dynamic processes are already taking place in it, ensuring the initiation of a secondary corona flash from it, and the locking effect of the corona cover charge is still relatively small. At streamer flash charges of ~4.4–7.2 μC, on the contrary, the effect of reducing the intensity of the external electric field of the stem region due to the action of the volume charge of the streamer corona itself plays an important role. At large values of the charge of the streamer flash flowing through the stem, electro-gas dynamic processes in it due to high energy release are so intense that the locking effect of the volume charge of the cover of the streamer crown no longer have any significant effect.

Figure 6 summarizes the results for primary streamer corona flashes for the entire experimental data array of the rod and extended electrodes: rod electrodes with tip radii from 0.05 cm to 3.5 cm (main data array for radii from 0.9 cm to 2.5 cm) and cylindrical electrodes with radii from 0.15 cm to 3.0 cm (main data array for radii from 0.55 cm to

1.75 cm). At different radii and different heights of the electrodes, the probability of a streamer flash passing into an ascending leader was determined, first of all, by the amount of charge flowing through its stem. However, the possibility of forming a streamer flash with a charge value related to the optimal range for moving into the ascending leader, of course, depended on the parameters of the electrode system.

Results correlate with the values of the streamer flash charges necessary for the emergence of a leader, as proposed in [2,12]. However, it was found that with these charges, the direct transition of the first pulse streamer corona stem to the upward leader is not always ensured. Moreover, as the value of the streamer flash charge increases, there is a tendency for the probability of its transition to the upward leader to decrease. This probability is minimal in the range of streamer flash charges 4.5 ÷ 7.2 μC.

Based on the processing of an extensive bank of experimental data, a probabilistic criterion for the occurrence of the upward leader from ground-based objects was proposed, and dependences of the probability of the occurrence of the upward positive leader on the value of the first pulse corona flash charge for model rod and elongated electrodes were established (Figure 6).

The figure shows that for the equal charge ranges of the first streamer flash formed in the electric field of an artificial thunderstorm cell, the probability of its successful transition to the upward leader from elongated model electrodes is somewhat higher than from rod model electrodes. The probability of the transition of a first flash into an upward leader is affected by the structure of the streamer corona, which is generally related to the character of the electric field near the grounded electrode, which in turn is determined by the shape of the corona electrode and the radius of its curvature.

3. Discussion and Analysis of the Particularities of Applying the Received Results to an Actual Thunderstorm Situation

Physical modeling of the processes of the occurrence of upward discharges from grounded objects in the electric field of an artificial lightning cell showed that the characteristics of the pulse streamer corona stem, its development, and transition to the upward leader section in the slowly increasing field of the artificial lightning cell depend significantly on the rod electrode tip radius or the cylindrical electrode radius.

When the size of the tip of a grounded rod or elongated electrode is significantly less than the critical values, there is practically no transition of the pulse streamer corona stem to the leader after the first streamer flash. It was experimentally determined that the probability of forming an upward positive leader from a grounded rod electrode in the electric field of an artificial thundercloud cell began to increase when the curvature radius of its apex exceeded 4–5 mm (for model elongated electrodes—2.5–3.5 mm). Similarly, it was noted in [42] that, when the radius of the curvature of the conical tip was a few mm, even at large overvoltages, no leader occurred after the initial corona flash.

The influence of the radius of the top of the lightning rod on the lightning capture distance is also predicted by the model of self-consistent emergence and the propagation of the upward leader [43]. It is supposed that the reason for the experimental observations, which show that "smooth" conductors are more effective in capturing the lightning than the sharp conductors, is due to the fact that there is an avalanche corona from the top of the sharp conductor during the time of lightning strike. For this reason, the radius of the conductor that appears to be best as a lightning interceptor depends on the height of the conductor and is better shifted from smaller radii to larger radii as the height of the conductor increases, i.e., in [43] it is supposed that there will not be any one critical radius, but an optimal range depending on external conditions, e.g., the height of a lightning conductor above the ground or above the main part of the object. It is estimated that an avalanche corona will occur for a 6 m high conductor (rod) with radii less than 0.5–0.75 cm, and at 20 m height, the critical radius will be 2 cm.

Referring to data from in situ experiments and observations, they concluded in [44] that smooth (blunt) tops in a certain range (with a top radius from 0.63 cm to 1.27 cm (better

~1 cm) are more favorable for initiating an upward leader than very sharp or strongly blunt tops. In [45], the same authors believe that there is an optimal rod tip radius (according to their calculations, the optimal radius is ~1–2 cm—10% more effective), which provides the maximal head height of the downward step leader, which can generate a stable (and unstable) upward leader from the rod.

In [46], using a similar principle and considering [47,48], an attempt was made to theoretically calculate the "optimal" radius for any lightning rod installed on a structure of any given size, considering as one of the important criteria the ratio of the field enhancement factor at the top of the rod to the radius of its top. By this factor, according to calculations [46], the optimum tip radius rarely exceeded 3 cm, even for relatively tall structures. It is considered that the optimum apex radii for vertical rods from 0.25 m to 10 m long installed on the ground surface or relatively low flat surfaces are in the range of 0.1 cm to 2 cm.

Thus, given that not all first streamer flashes transition into the leader, it makes sense to move this "optimal" zone along the top curvature (wire) radii to initiate the upward leader; compared to [43], even a little more to the right.

Formation of an upward leader after the first streamer corona flash without a pronounced dark pause is one of the key factors in ensuring the efficiency of a lightning rod, since an early start and propagation from it of the upward leader will significantly reduce the probability of the formation of competitive upward leaders from structural elements of the protected object, and, therefore, the probability of their being struck by lightning.

As noted above, it is assumed that the initiation of an upward leader after a first pulse corona flash can occur from electrodes whose curvature radius exceeds several centimeters and the streamer flash charge exceeds some critical value (~1 μC) [2,12,41,49–51]. Experiments using artificial thunderstorm cells showed that the value of 1 μC is only one of the possible special cases. The fact that the flash charge value of a pulse streamer corona, at which the leader was launched successfully, can differ significantly from the 1 μC value indicated was also established by experiments in long air gaps [41,52,53]. Streamer flash charges in a range from 0.23 μC to 1.2 μC and more were recorded, which were already sufficient for leader initiation. In the model [54], the critical charge required for the direct transition of the first streamer corona into the leader at electrodes with large radii of curvature is estimated to be much lower (between 0.08 μC and 0.5 μC per stem) and associated with the given size of the stem cross section. Similar estimations were made in the construction of models of rising leader emergence. In [12,15] the critical charges of streamer flash were given in the range of 0.2 μC to 1.0 μC.

Experiments using an artificial thunderstorm cell of negative polarity established that the probability of initiation of the upward leader is determined not only by the value of the total flowing charge, but also by the duration of the time interval during which the flash current was at a level close to the maximum value and has a complex dependence character on the value of the primary streamer flash charge. This is indirectly confirmed by experiments in long air gaps [42,47,52,55], where primary streamer corona flashes with amplitudes of 2–5 A, but with current durations of more than half the maximum of several hundred nanoseconds, did not lead to the formation of an upward leader. The streamer flash charges from electrodes with the apex curvature radius from 0.5 cm to 2.5 cm could be in the range of 0.6 μC to 3 μC [47].

4. Conclusions

Physical modeling of the processes of the occurrence of upward discharges from ground objects in the electric field of an artificial thunderstorm cell revealed a significant influence of the rod and elongated electrode tip radii on the parameters of the first pulse corona stem and on the probability of its transition to an upward leader. It was found that the tip radii of model rod electrodes from 1.5 cm to 3.0 cm and the radii of model elongated tube electrodes from 0.7 cm to 1.75 cm allow for the most probable formation of a first pulse streamer corona with such parameters that provide the best conditions for starting the upward leader without a pronounced dark pause.

A significant difference in the characteristics of a pulse streamer corona for the case of a transition of its stem into an upward leader and for the case of no such transition was established. It is shown that the value of the first streamer flash charge is not strictly a threshold criterion for the appearance of the upward leader from a ground-based object, and only determines the probability of its appearance. It was established that, under conditions of a slowly growing field of an artificial thunderstorm cell, the determining factor in the possibility of transition of the first pulse corona stem into an upward leader is not only the total pulse corona flash charge flowing through the stem, but also the duration of the time interval during which the primary corona flash current is at a level close to the maximum.

On the basis of an extensive bank of obtained experimental data, we established the dependences of the probability of occurrence of the upward positive leader on the value of the first impulse corona flash charge for rod and elongated electrodes. A probabilistic criterion for the appearance of an upward leader from ground objects in the electric field of a thundercloud and a negative downward leader of lightning was proposed based on analysis of the particularities of applying the received physical modelling results to an actual thunderstorm situation. The obtained results and the identified trends can be used both in the development of a mathematical model of the processes of occurrence of upward (opposite) leaders from lightning rods and protected objects under thunderstorm conditions and to modify the methods of calculation for the protection of ground objects from direct lightning strikes.

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