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TOWNSEND STAGE OF NEGATIVE CORONA DISCHARGE IN ATMOSPHERIC AIR

E.Kh. Baksht, A.G. Burachenko, A.N. Panchenko

Institute of High Current Electronics SB RAS,
634055, Russia, Tomsk, Akademichesky Ave., 2/3

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Abstract. Low-current Townsend stage of negative corona discharge in air and conditions of its occurrence were studied. This stage can occur in the range of applied voltage lower than the voltage characteristic for Trichel pulse generation. Effect of various factors on the Townsend stage occurrence was studied. Experimental conditions facilitating observation and study of the Townsend stage were found. Current-voltage characteristic of the Townsend stage of the corona discharge was obtained, and photographs of the glow of this stage were taken. An explanation was proposed for the causes of occurrence or absence of the Townsend stage during ignition of a negative corona discharge.

Keywords: negative corona, Trichel pulses, dark Townsend discharge.

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Corresponding author: Baksht Evgenii Khaimovich, beh@loi.hcei.tsc.ru

Introduction

A corona discharge is a self-sustained in a non-uniform electric field, as is well known. From the point of view of technical applications, the most popular is a negative discharge in air at atmospheric pressure. This discharge has a number of features that continue to arouse interest and questions among researchers. One of these features is behavior of the corona discharge near threshold the Trichel pulse (TP) generation [1]. TPs are short current pulses with an amplitude of $\sim 1\text{--}10$ mA, occurring in a certain voltage range during ignition of a negative corona discharge in electronegative gases.

The low-current stage preceding the TPs has long been the subject of attention [2, 3], but different research groups estimate the maximal current in this stage from 0.1-1 nA [2, 4, 5] to 0.1-1 μA [6-9]. The assumption that the corona discharge current at this stage has a field emission nature is substantiated in [5]. In [6-9] this low-current stage is called as Townsend stage. The Townsend stage in the ignition of a corona discharge is discussed in [10] and is mentioned in [11]. Current in this discharge stage was not recorded within the measurement error of ± 0.2 nA under conditions of our previous experiments [12]. Therewith it was found that the TP mode could become unstable in a certain voltage range starting near the TP generation threshold, when the TP mode is periodically replaced by a low-current pulseless stage of corona discharge [12]. The quasi-stationary current of the pulseless stage was of the same order as in [6-9], therefore, in what follows, we will also call this stage the Townsend stage (TS). The aim of the work is to find out whether TS can arise immediately upon ignition of a corona discharge and which factors contribute to this.

1. Experimental equipment and measurement techniques

The behavior of the corona discharge near the TP generation threshold was studied using the experimental setup schematically shown in Fig. 1. When igniting a negative corona discharge, the electrode configurations point (cathode)-to-plane (anode) and point-to-point were used. The discharge was ignited in atmospheric air. Discharge gap d varied depending on the electrode configuration: 10-20 mm for the point-to-plane configuration and 1-5 mm for the point-to-point configuration.

Capacitance C_p damped large peak TP's current and allowed recording a quasi-stationary current under conditions where the amplitude of the signal under study could change by 4 – 5 orders of magnitude. Shunt resistance R_3 was 0.1 MOhm. The voltage was supplied to the electrodes from a high-voltage source through ballast resistance R_b , which could vary from 3 to 940 MOhm depending on the experimental conditions. The high-voltage source produces a voltage in the range (0 – 5) kV with a step of 10 V. The source also allowed the voltage to be automatically increased to a given value at a constant rate of ≈ 400 V/s.

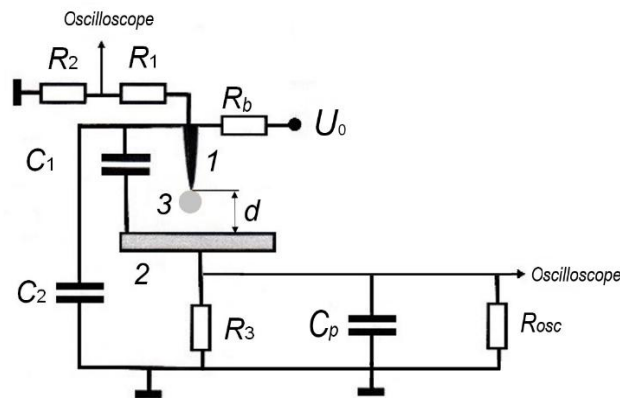


Fig. 1. Schematic diagram of the experimental setup. (1) cathode (point); (2) anode (flat electrode); (3) corona discharge glow region.

The cathode was steel needles with a nickel coating 4-5 μm thick. Diameters of the needles were 0.4 – 1 mm, the point rounding radii $r = 20 - 60$ μm .

The voltage across the gap was measured using a TT-HVP 2739 high-voltage probe (R_1 and R_2) with a bandwidth of 220 MHz. Electrical signals were recorded using an MDO 3104 oscilloscope (1 GHz, 5 samples/ns). The signal from the R_3 resistor was fed to the oscilloscope via a 50-Ohm cable 1 m long. A 50-Ohm or a MOhm oscilloscope input was used in different studies. When using a megohm input and discharge currents of $\lesssim 0.3$ mA, the current recording system was an integrating circuit with a time constant of $R_3 C_p$. Therewith time resolution of the current recording system was significantly reduced, but this did not affect the accuracy of recording the quasi-stationary current, which in these conditions was the dark Townsend current [6-9], preceding the first TP. Besides, information about the appearance of the TP was

obtained, as well. The measurement set-up made it possible to record a quasi-stationary current of ≥ 2 nA.

To reduce high-frequency noise, the oscilloscope bandwidth was decreased to $\Delta f_{osc} = 20$ MHz, which resulted in a decrease in the oscilloscope time resolution to ≈ 20 ns. All changes in the recording system were aimed at measuring currents less than 1 μ A and not affecting the current amplitudes at pulse durations much longer than $R_3C_p = 11.7$ μ s, including the quasi-stationary current of the dark Townsend discharge. Pulses with a duration of $\sim R_3C_p$ and less were distorted in shape and decreased in amplitude, but could also be recorded.

All measurements were performed with control of temperature, relative humidity and atmospheric pressure in the room, while changes in temperature and humidity were insignificant (22°C-24°C and 18 %-24 %, respectively). Photographs of the cathode discharge region were taken using a long-focus microscope K2 DistaMax. To measure the radii of rounding of the needle points and other geometric parameters of the needles, an optical trinocular digital microscope Saike Digital SK2009 was used. To study the elemental composition and surface relief of the needle point, a Quanta 200 3D scanning electron microscope manufactured by FEI Company (USA), located in the Tomsk Regional Center for Collective Use, was used.

2. Experimental results and their discussion

2.1. Point-to-plane electrode configuration

To study the unstable mode of TP generation, it was necessary to obtain good reproducibility of this discharge mode. At first experiments were performed using the point-to-plane electrode configuration, the gap was 20 mm. During the experiments, it turned out that the instability of the TP mode, during which TS appears, occurs quite rarely and can spontaneously disappear. In the range of voltages characteristic for TPs, TS appeared within a fairly long time interval after the ignition of the corona discharge and its maintenance at a voltage across the gap of $U_0 = 3.5$ -4.5 kV. The appearance of TS was expected within 2-2.5 hours, and then the needle were changed. Instability of the TP mode with its transition to TS and back appeared approximately once per

5-7 identical tested needles. In this case, the delay time for TS to appear could be from 15 min to 2.5 hours.

The TS appeared after its first occurrence with each repeated switching on the high voltage. The upper limit of its existence was in the voltage range of 3-4.5 kV. The lower voltage threshold was 2.7-2.9 kV, but there were quite often cases when, when the voltage increased to the threshold value of corona discharge ignition, the TPs were completely absent and a steady current immediately arose, similar to the results presented in [6-9]. As a rule, this occurred in the case of switching off the voltage and switching it on again after a short time ($\lesssim 1$ min). When switching on the voltage after a few minutes, the TP first appeared in the voltage range of 2.7-2.9 kV, and then, with a further increase in voltage, the TS was evident.

The TS was obtained using needles with a point rounding radius of 20-40 μm . Waveforms of the unstable TP mode are shown in Fig. 2a. Fig. 2b depicts waveforms of the TS occurring immediately upon ignition of the corona discharge, as described above. The current-voltage characteristic (CVC) of the TS is shown in Fig. 3. It is evident that the CVC of the TS has an increasing character.

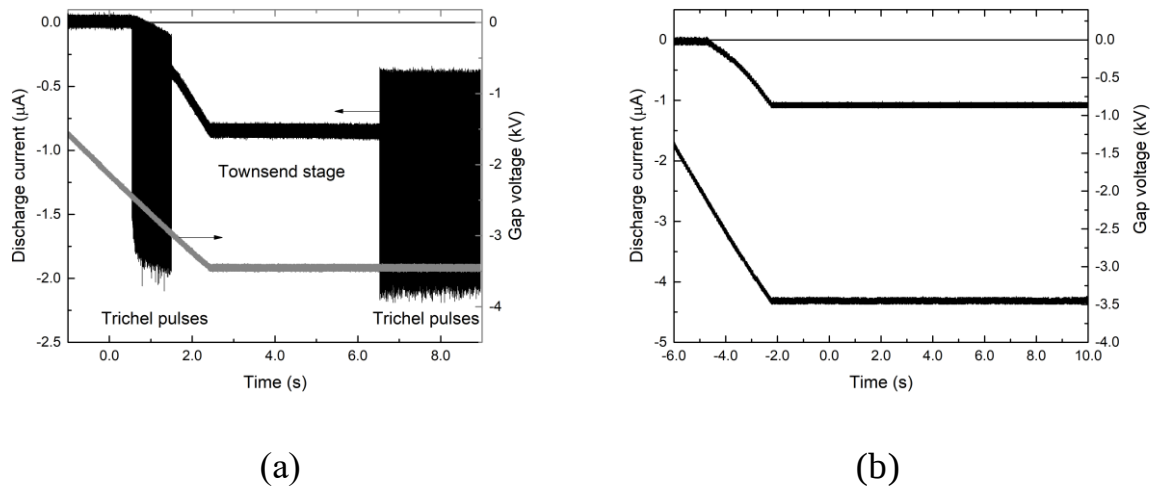


Fig. 2. Waveforms of discharge current and voltage across the gap.
(a) – unstable TP mode, (b) – beginning of corona discharge with TS.

Point-to-plane configuration of electrodes is used,
 $d = 20$ mm, $r = 20$ μm , $R_b = 3$ MOhm.

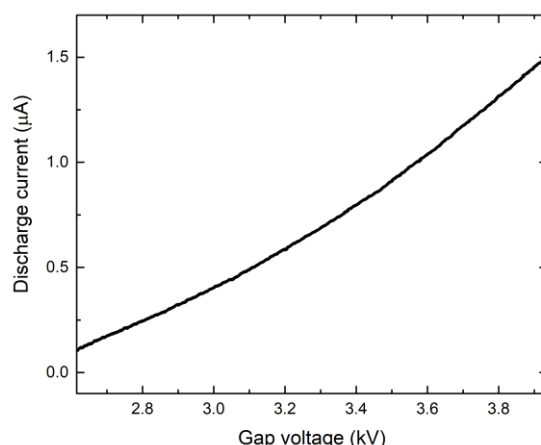


Fig. 3. CVC of corona discharge Townsend stage.

Point-to-plane configuration of electrodes is used, $d = 20$ mm, $r = 20$ μ m.

Photographs of the glow of regular TPs and TS corona discharge were also taken (Fig. 4). These images clearly show the differences between these two corona discharge modes. In the regular TP mode (Fig. 4a), the discharge glow contains clearly distinguishable glowing areas – negative glow and positive column, separated by Faraday dark space. A similar glow structure was observed in [2, 6, 13].

In the case of pulseless discharge mode at a voltage preceding the voltage of TP occurrence, the corona discharge glow (Fig. 4b) includes one glowing region tied to the region with maximal amplification of the electric field on the cathode. The glow pattern and the level of the discharge currents allow us to assume that a dark Townsend discharge is observed, which in a sharply non-uniform electric field in atmospheric air can glow in the region of the strongest electric field [14].

It should be noted that the images of the TS glow were obtained for the first time. In scientific literature, only photographs of a corona discharge glow in TP mode are provided.

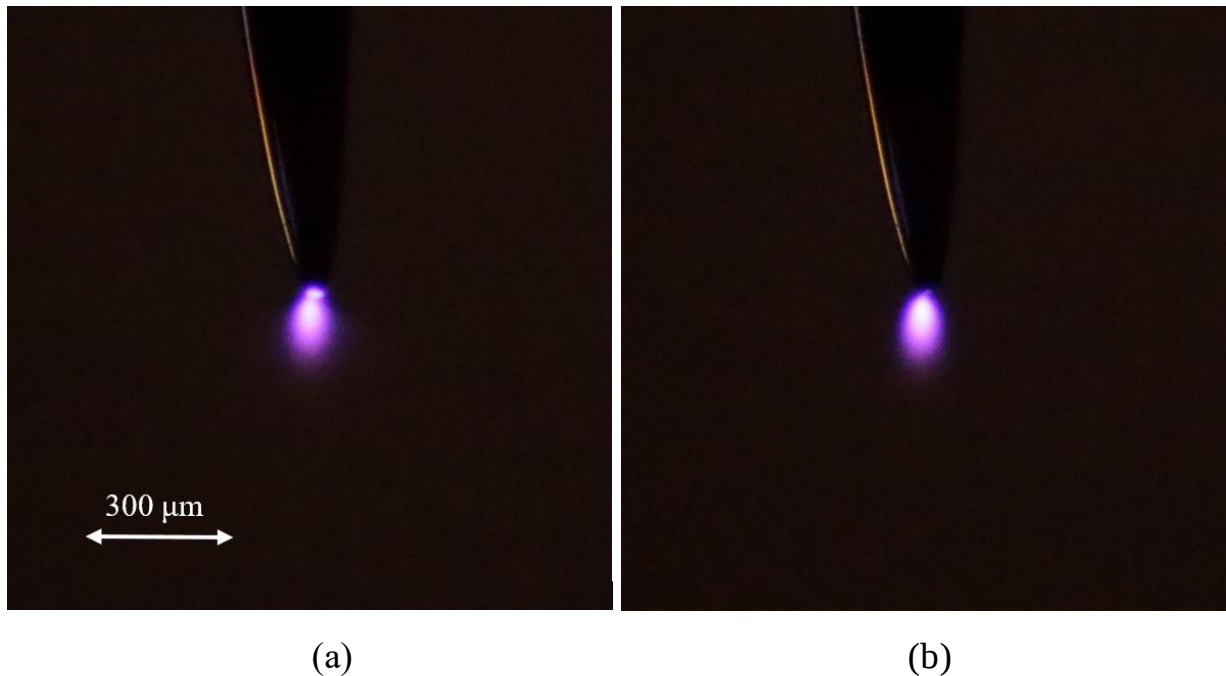


Fig. 4. Photographs of corona discharge glow.
 (a) – regular TP mode, (b) – corona discharge TS.
 Point-to-plane configuration of electrodes is used,
 $d = 20$ mm, $r = 20$ μm. Exposure time is 2 s.

In order to understand the difference between the needles with which TS was observed and the same needles with which this effect was not observed, the surface and elemental composition of the needle points were studied using a scanning electron microscope. The following were studied: needle N1, with which TS was obtained, needle N2, with which the effect appeared and then disappeared, and needle N3, with which the effect was not obtained in a corona discharge for two hours. The study showed that in the composition of the surface layer of nickel (4-5 μm thick) at the very top of the tips of these needles there are small areas with characteristic dimensions of ~10-15 μm with a relatively low oxygen content, which characterizes the thickness of the nickel oxide film: 4.3 At% for needle N2 and 6.7 At% for needle N3. For needle N1, oxygen was not detected. On the periphery of the point of all three needles there were separate areas with oxygen content up to 20-30 At%, there were areas with high carbon (it characterizes contamination) and aluminum content. Low content or absence of oxygen in small areas on the point tops is associated with surface cleaning in the place of the main corona discharge binding. For the N3 needle, as a significant difference in the surface relief, one can point out the presence of a protruding part of

the exfoliated nickel coating with a height of $\approx 10 \mu\text{m}$ and a width of $\approx 30 \mu\text{m}$ at a distance of $\approx 50 \mu\text{m}$ from the point top.

2.2. Point-to-point electrode configuration

Since it was quite difficult to obtain the TS stage of the corona discharge, measures were taken to facilitate its occurrence. For this purpose, the corona discharge was ignited in the point-to-point gap. Therewith in short gaps (of the order of several millimeters), the conditions for the occurrence of a self-sustained discharge are facilitated due to the development of avalanches under more favorable electric field than for the point-to-plane configuration with the same gaps and voltages. Under these conditions, a greater number of ions hit the cathode, which leads to an increase in the flow of secondary electrons arising due to ion-electron emission. Some increase in the number of secondary electrons is also possible due to the enhancement of photoelectron emission in such electron configuration. As a result, the point-to-point system becomes more sensitive to changes in the emission properties of the cathode – the conditions for the occurrence of a dark Townsend discharge are facilitated.

In the experiments with corona discharge in the point-to-point configuration, needles with a diameter of 0.4 and 1 mm with a point rounding radius of $r \approx 20 \mu\text{m}$ or $r \approx 60 \mu\text{m}$, respectively, were used as the cathode. A needle with $r \approx 20 \mu\text{m}$ served as the anode. When using a 0.4 mm N2 needle with $r \approx 20 \mu\text{m}$ as the cathode, on which the corona discharge TS was obtained in the point-to-plane electrode configuration and then stopped, in the point-to-point configuration TS was again observed, but the currents of this stage were generally lower than in the point-to-plane configuration. Therewith TS was not observed at all for any gaps and voltages in the point-to-plane electrode configuration. Typical waveforms of the TS current and voltage are shown in Fig. 5a.

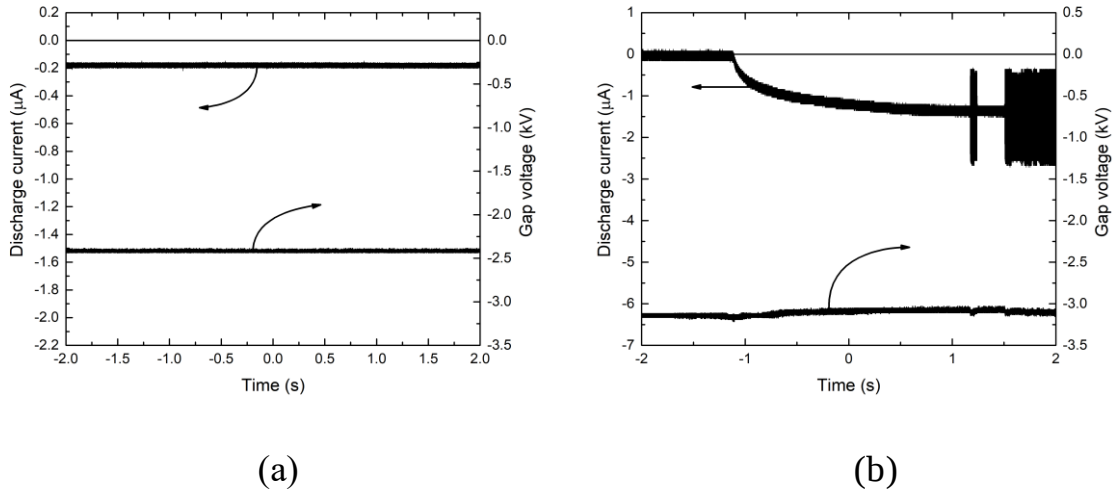


Fig. 5. Waveforms of discharge current and voltage across the gap.
Point-to-point configuration of electrodes is used,
 $d = 4$ mm, $R_b = 100$ MOhm. (a) – $r = 20$ μ m, (b) – $r = 60$ μ m.

When the gap d was shortened from 5 to 2 mm, the maximum current of the TS during corona ignition (before the appearance of the TP) first increased from ≈ 20 nA ($d = 5$ mm) to 150-200 nA ($d = 4$ mm), and then decreased to 110-120 nA ($d = 3$ mm). With a gap of $d \approx 2$ mm, spark breakdowns of the gap often occurred. Such behavior of the TS current can be explained by an increase in the influence of the second point on electric field configuration in the gap with a decrease in the gap from 5 to 4 mm, and with the achievement of the critical field strength required for the TP generation of at $d = 3$ mm, at lower voltages than at $d = 4$ mm.

In the point-to-point configuration, TS was also observed for new needles that had not been used as electrodes before. However, on some new needles, TS was not observed and TPs appeared immediately. Nevertheless, after working with one of these needles (N4) in $d \approx 2$ mm for a short time (~ 10 s) in the spark breakdown mode and then increasing the gap to 3 mm after a short period of work in the TP mode, TS appeared.

Experiments were also performed in the point-to-point configuration with a N5 needle of 1 mm diameter and $r \approx 60$ μ m. At first, a TS with a maximum current of ≈ 75 nA ($d = 4$ mm) was obtained. However, after operation at $U_0 = 5$ kV for 5 min, a TS with peak current of ≈ 1.5 μ A appeared at the gap voltage of 3.24 kV. The current and voltage waveforms for this case are shown in Fig. 5b. Photographs of this needle

(Fig. 6), taken with an optical microscope showed that the additional nickel protrusion on the point (a defect in the shape of the point) of height $h = 7 \mu\text{m}$ and $r = 2.7 \mu\text{m}$ almost completely disappeared after operation. The next day after a short operation, the TS disappeared and only the TPs were observed.

Images of the TS and TPs glow in the point-to-point configuration, taken using a long-focus microscope, are shown in Fig. 7. It is evident that the glow pattern for both modes qualitatively coincides with similar ones in the point-to-plane configuration (Fig. 4).

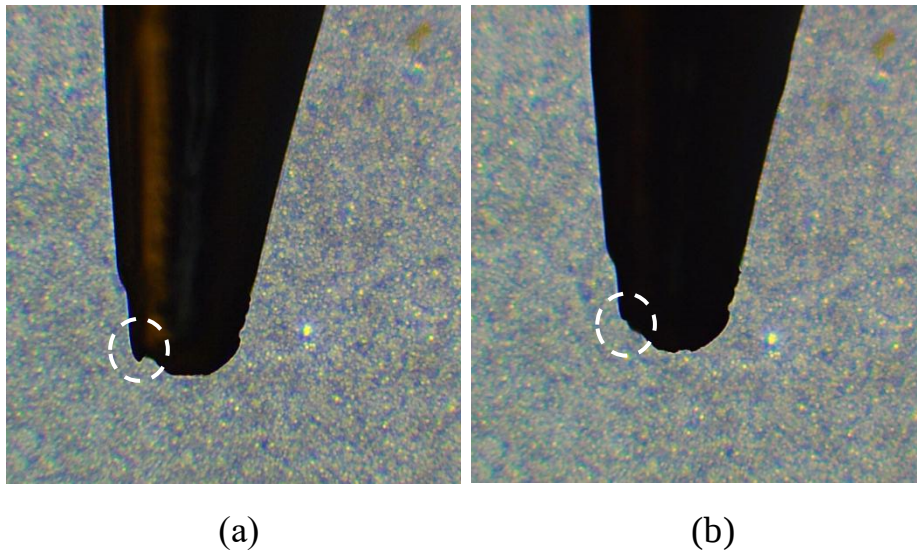


Fig. 6. Photos of the needle electrode before (a) and after (b) operation for 5 min at $U_0 = 5 \text{ kV}$. Nickel protrusion (a defect in the shape of the point) of height $h = 7 \mu\text{m}$ and $r = 2.7 \mu\text{m}$ almost completely disappeared after operation and maximum current of TS increased from 75 nA to 1.5 μA . The protrusion area is outlined with a dotted line. Point-to-point configuration of electrodes is used, $d = 4 \text{ mm}$, $r = 60 \mu\text{m}$, $R_b = 100 \text{ MOhm}$.

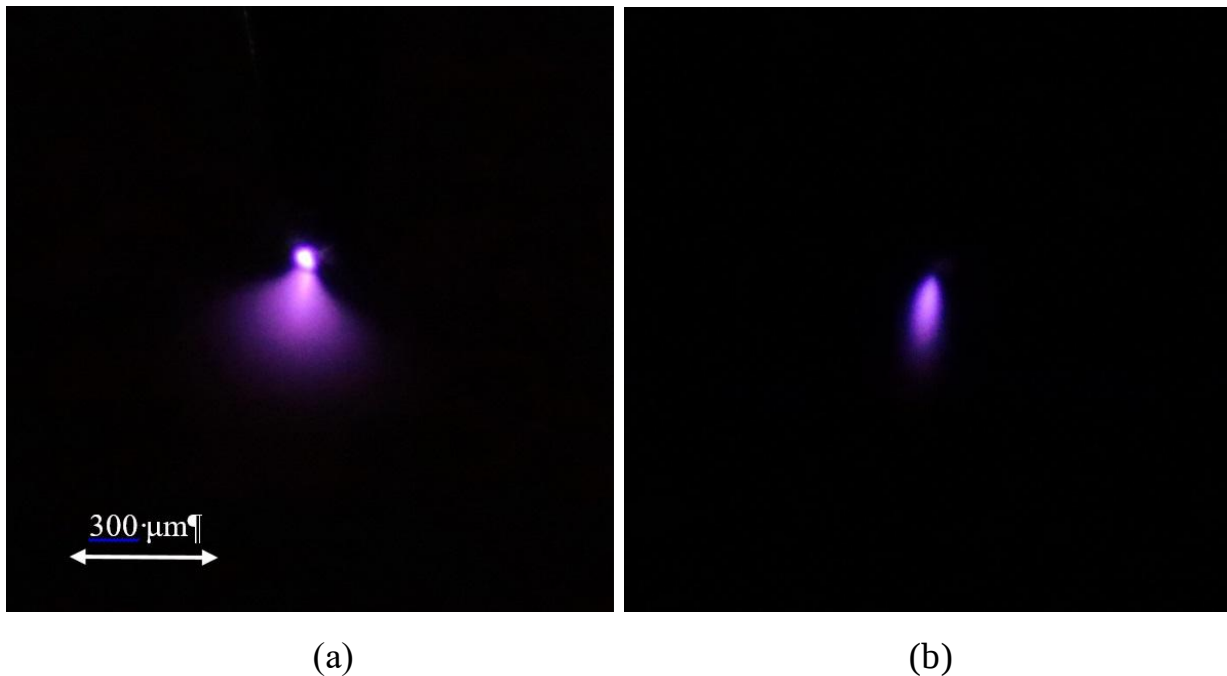


Fig. 7. Photographs of corona discharge glow.

(a) – regular TP mode, (b) – corona discharge TS.

Point-to-point configuration of electrodes is used, $d = 4$ mm, $r = 60$ μm .

Exposure time is 0.25 s.

2.3. Glow discharge treatment of electrodes

Since the most probable cause of the TS appearance is a change in the emission properties of the point, attempts were made to affect its surface with a glow discharge in low pressures of air or argon (the point was the cathode). In this case, the glow discharge treatment allows cleaning the electrode surface and smoothing its microrelief [15-17]. However, treatment the points in the glow discharge gave ambiguous results in the point-to-plane configuration.

Treatment in air at 7-10 Torr and currents of 3.5-3.8 mA during more than 15 min resulted in a sharp increase in the threshold voltage of the corona discharge ignition U_{th} (from 2.3-2.5 to 3.8 kV for needles with $r \approx 20$ μm in the point-to-plane configuration, gap $d = 20$ mm), which then gradually decreased during operation time. In this case, the TS in the corona discharge was not observed. However, 5 min of needle treatment, for which only TPs were observed within 2 hours of operation, led to the appearance of TS. The TS appeared after 1-3 min voltage was applied at the gap. However, the result was not repeated with another similar needle.

Needle treatment in a glow discharge in argon allows one to minimize the influence of contamination and oxide films, but only before the beginning of the generation of the first TP. Nickel coating is almost not oxidized at room temperature, oxides begin to form at a temperature of several hundred degrees. However, during operation its surface can again be covered with oxide films and microparticles due to the erosion of the cathode material during the generation of TPs [13, 18].

Treatment in argon at 30 Torr and a current of 3.8 mA for 5 min resulted in a sharp increase in U_{th} (from ≈ 3 to 4.5 kV) for a N5 needle with $r \approx 60 \mu\text{m}$ in the electrode configuration point-to-point and $d = 4$ mm. The TP discharge mode was evident. After several minutes of operation, U_{th} dropped to 3.5 kV and TS was not observed. A day later, after a short operation in the TP mode, TS appeared again with a current of ~ 100 nA, as before the treatment.

Several needles with $r \approx 20 \mu\text{m}$ were also treated in the glow discharge in argon. Treatment was performed with the same glow discharge parameters as for the N5 needle. When treating one of the needles for the point-to-point configuration, the TS mode was maintained until the nickel coating was completely removed from the point's apex. For other needles, the TS mode was also maintained after treatment in argon for 10-20 min.

When operating with the N6 needle ($r \approx 20 \mu\text{m}$), for which the TS was not observed at $d = 3-4$ mm, and the TP mode immediately appeared upon reaching $U_{th} = 2.22$ kV. The corona discharge mode did not change after treatment in argon for 20 min, but U_{th} increased to 2.33 kV. However, when the gap was reduced to $d = 2$ mm (short-term influence on the point surface by spark breakdowns) and then the gap was increased to $d = 3$ mm, TS appeared. It appeared after the discharge was ignited in the TP mode and the voltage was forced to decrease across the gap until the TPs disappeared at $U_1 = 1.9 - 2.1$ kV. Further voltage decrease led to decrease of the recorded steady-state corona current to zero. In this case, if the voltage was greater than a certain critical value ($U_c \approx 1.7 - 1.8$ kV for $d = 3$ mm), then as the voltage increased, the steady-state corona current began to register again. This indicates that at a voltage of $\sim U_c$, the Townsend current was still flowing in the gap, although it was already

below the registration threshold. When the voltage was forced to decrease to a value below U_c , the corona current disappeared and the TP mode immediately arose when the voltage is increase again. It is obvious that when a voltage across the gap $U < U_c$, the condition for the self-reproduction of the avalanches is no longer satisfied.

The experiment with the N6 needle, for which the TP mode immediately appeared when the voltage across the gap increased, and the TS mode appeared when it decreased below U_1 , shows that when voltage $U_2 < U_1$ the corona discharge continues to be supported by a steady-state current, since the condition for the self-reproduction of avalanches is satisfied at this voltage. However, if the same voltage (U_2) is applied to the “cold” gap (in which there was no discharge), corona discharge does not ignite because there are no initial electrons initiating the discharge in the vicinity of the cathode. With a further increase in voltage to U_{th} , the corona discharge will ignite in the TP mode, since the initial electrons will appear, for example, as a result of field emission in the presence of dielectric films and inclusions (estimates for our experimental conditions give a value of the electric field strength at the cathode point $E \sim (2 - 4) \cdot 10^5$ V/cm, which is sufficient for the emission). If the initial electrons for some reason appear near the cathode at voltage U_2 , a stationary discharge will ignite. In accordance with the above, we believe that the appearance of the TS under conditions characteristic of the waveforms in Fig. 3 is most likely associated with the Malter effect [19] and/or exoelectronic emission [20-22]. Both effects can provide electron emission even in the absence of an electric field (the emission decreases and then disappears with time). Exoelectronic emission can occur during electrode erosion in a discharge [23]. Cathode erosion in a corona discharge during the generation of TPs was observed, for example, in [13, 18]. The results of experiments with needle N4 (the appearance of the TS after a series of breakdowns) and with needle N5 (an increase in the TS current to ≈ 1.5 μ A with the disappearance of an additional protrusion on the cathode point during operation) testifies in favor of the appearance of initiating electrons as a result of exoemission. Nevertheless, both effects can serve as suppliers of initial electrons at voltages characteristic of the TS during the ignition of a negative corona discharge.

Conclusion

A study of the Townsend stage of negative corona discharge and the conditions of its occurrence was performed. The results obtained are often difficult to interpret, since they can be influenced by a large number of different difficult-to-control factors. However, the following conclusions can be made:

The Townsend stage of the corona discharge preceding the TP and discussed in [6-9] was observed in our experiments and coincides with the data of [6-9] in terms of current levels. Under the conditions of our experiments, TS occurs quite rarely and usually alternates with the generation of TPs within the same voltage range. Therewith, under certain conditions (for example, when the discharge is re-ignited after a short period of time), the corona discharge can begin with a TS, which will last for quite a long time (up to several minutes or more), if a certain threshold voltage (depending on the state of the cathode surface) at which TP appears is not exceeded. We believe that the most probable cause of the appearance of TS during the ignition of a negative corona discharge is the early appearance of the initial electrons in the immediate vicinity of the cathode point due to the Malter effect and/or the presence of exoelectronic emission arising due to the erosion of the cathode point. If the initial electrons are absent near the cathode, the TS is not formed, while initial electrons appear at higher voltages due to another processes.

Experimental conditions have been found facilitating the observation and study of the TS. This is the ignition of a corona discharge in the configuration of electrodes point-to-point.

It has been shown that the current-voltage characteristic of the pulseless stage of the corona discharge has an increasing character.

It is shown that the glow of the TS of corona discharge is uniform and differs from the glow of the TP mode, which has a structure similar to the structure of a glow discharge. Photographs of the TS were obtained for the first time.

So far, the initial experiments have been made, which have answered only some of the questions. A number of questions, and first of all the question of the physical mechanism that allows the existence and periodic replacement of the low-current TS

and the “high-current” stage of the TP mode at the same voltage at the gap, require further study.

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