Interaction of corona discharge with surface layer of metal

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Abstract. Properties of the corona discharge containing a conic electrode were researched. The main modes and characteristics of this discharge were researched. There are current oscillations of the discharge within the range of 1 kHz - 150 MHz. Possible oscillation and wave processes are considered to explain these oscillations. Emergence of rotation motion when the discharge affects the dielectrics is being studied. The effect of this discharge on metal surface was explored.

1. Introduction
The corona discharges normally have weak currents within the microampere units' range at voltages on the order of tens of kilovolts, and have quite subtle glowing. One of the unusual properties of the corona discharge is appearance of high-voltage oscillations within the kilohertz range first identified in work [1]. Oscillation processes with frequencies up to hundreds of megahertz display during the works on the study of the corona discharges [2,3]. When the current is increased up to 100 μA, the discharge acquires new properties that are not inherent to the typical corona discharge. The corona discharge in the system of conic and flat electrodes was studied in this work. When the discharge is burning, there are areas that are in immediate contact with the metal surface. The possibility of using corona discharges for modification of surfaces of various materials was assessed in the works [4]. The rotation properties of the dielectrics were studied the corona discharge environment.

2. Experimental setup
The experimental unit for research of the corona discharge is reviewed in figure 1. The conic electrode (diameter - 2-6 mm, cone angle - α=15°-25°) was made of steel or copper, and the cylindrical electrode was made of aluminum or steel (diameter - 35-45 mm, thickness - 10-15 mm). The electrodes were positioned at the distance of 0.5-45 mm. A high-voltage power source with 1-27 kV voltage and up to 2 mA current was used. The discharge had more stable combustion when positive polarity was applied to the conic electrode. The discharge voltage was measured using a static kilovoltmeter, and the current in the circuit was measured with a microammeter. A Nikon 1 G camera (time resolution is 1 ms) was used for recording of the discharge image. The corona discharge images for the two main discharge modes are provided in figure 2. The glow normally has dark light blue or violet color, and the intensity of the glow is quite feeble. Within the current range of I=1-40 μA, this corona discharge has a practically cylindrical shape (figure 2a) with a diameter of 1-2 mm and a length equal to the inter-electrode space of 0.5-5 mm. At great currents within the area of I=60-150 μA, the discharge
may have a branched shape (figure 2b). These corona discharge modes have various electrical characteristics.

The dependence of voltage $U$ on distance between the electrodes $d$ within the value range of $U=1.5-3.5$ kV and $d=0.5-5$ mm is approximately linear. In this case, the current of the discharge falls within the range of $I=1-40$ μA. The volt-ampere characteristics of the discharge in this mode is described through a quadratic dependence [5]:

$$I = \frac{8\pi c_0 \mu U (U - U_K)}{(d^2 \ln(d/r_0))}.$$ 

The value of $U_K$ is found from the formulas:

$$U_K \approx E_K r_0, \quad E_K \approx 31 \delta (1 + 0.308/(\bar{\delta}_0)^{1/2}) \text{ kV/cm} \quad (\delta = p/p_n, \text{ p-pressure, } p_n\text{-pressure in normal conditions})$$

and equal to $U_K=1.9$ kV at the anode curvature radius of $r_0=0.05$ mm.

As voltage increases in the discharge gap within the range of the values $U=4-20$ kV and if the distance between the electrodes is $d=5-40$ mm, the amperage of the discharge rises up to the values within the range of $I=70-150$ μA. The form of the volt-ampere characteristics in this range is approximately linear. The structure of the discharge in this mode acquires a branched form consisting of two or more thin channels. These spark channels come out of the anode tip and branch across the cathode area of about 10-15 mm in diameter. The combustion of the discharge may acquire unstable behavior, and then the current experiences pulsing at a frequency of 0.5-1 Hz.

3. **Research of electrical oscillations**

In order to study the oscillation processes, electrical and magnetic probes, signals from which were delivered to Tektronix TDS 2024V oscilloscope running in the frequency analyzer mode, were used in the work. Electric probes were metal rods 5-10 cm long and 1-5 mm in diameter. Coils (3-5 mm in
diameter, the number of turns is 150-250, wire thickness is 0.1 mm) placed in protective dielectric cases were used as magnetic probes. Electric probes were placed at the distance of 0.3-1.0 m from the discharge. The magnetic probes were positioned both in immediate proximity to the discharge, 0.2-0.5 m away from the discharge. According to these measurements, the current in the discharge circuit is a sequence of pulses following at frequency of \( v = 1 \text{-} 20 \text{ kHz} \). In order to get the measured pulse frequency distribution, the frequency analyzer mode of the used oscilloscope was utilized. The following frequencies were the main ones: 4.8±0.2 kHz, 39±2 kHz, 87±4 kHz, 228±11 kHz, 3.5±0.2 MHz, 12±0.6 MHz, 26±1 MHz, 32±2 MHz, 63±3 MHz, 85±5 MHz, 91±5 MHz. The spectrum of electric oscillations of the corona discharge is presented in figure 3a. An separate pulse has a peak form with the leading front having the duration of 10-20 \( \mu \text{s} \) and a decay on the trailing edge having a duration of 150-350 \( \mu \text{s} \) (figure 3b). An oscillation process with a higher frequency of \( v = 100 \text{ kHz} - 200 \text{ MHz} \) emerges in the background of the pulse.

![Figure 3](image-url)

**Figure 3.** Electric oscillations of the corona discharge: a) the spectrum of current oscillations, b) the characteristic time dependence of the current pulse

For the values of plasma concentration in the corona discharge \( n_e = 10^4 \text{-} 10^{10} \text{ cm}^{-3} \), the range of plasma frequency values \( \omega_p = (4\pi n_e e^2/m_e)^{1/2} \) will be in the following range: \( \omega_p = 5.5 \cdot 10^6 \text{-} 5.5 \cdot 10^9 \text{ s}^{-1} \). According to the conducted measurements, the lower concentrations of values of electronic concentration \( n_e = 10^4 \text{-} 10^6 \text{ cm}^{-3} \) exist near the flat surface of the electronic cathode [2]. Higher concentration values \( n_e = 10^7 \text{-} 10^{10} \text{ cm}^{-3} \) are present in the area that surrounds the tip of the conic anode where electron avalanche start. In view of this, the originating oscillations of this discharge within the range of \( v = 1 \text{-} 100 \text{ MHz} \) can be associated with excitation of a high-frequency plasma wave in the environment of the corona discharge [6].

Great interest has been currently shown to materials having new reflective properties in the optic and high-frequency ranges of electromagnetic radiation [7]. These characteristics are connected with consideration of effects taking place in thin micron films on the surface of the solid. Due to the dispersion law for electromagnetic waves plasmon waves can exist in the metal at frequencies that are lower than the plasma frequency \( \omega_p = (4\pi n_e e^2/m_e)^{1/2} \) \( n_e \) – concentration of electrons in metal). These waves can spread in thin films with a thickness of 1-50 \( \mu \text{m} \). According to these ideas, excitation of the plasmon waves with the frequencies in the area of \( v = 40 \text{ kHz} \text{-} 250 \text{ MHz} \) is possible in the thin superficial layer of the conic anode in case of the corona discharge. Lower frequencies within the range \( v = 1 \text{ kHz} \text{-} 150 \text{ kHz} \) can correspond to the sound plasmons area.
4. Investigation of the surface of electrodes

The maximum density of current in the construction of this corona discharge is achieved near the tip of the conic anode and on the flat surface of the cathode contacting with the discharge. Gray deposits are formed on the anode surface (material: steel, copper) near the tip during the work of the corona discharge. The surface of the electrodes was researched using Hitachi TM1000 electronic microscope. The image of the steel anode surface at a distance of about 0.2 mm from the tip is presented in figure 4. The effect of the corona discharge is expressed in appearance of hollows and stripe-like structures on the surface. The hollows have a medium size of 0.5-1.0 μm and an irregular elongated shape with the average quantity of 15-20 in the area of 100 μm². The stripes are located on the surface in the direction that is predominantly perpendicular to the generator of the cone and have thickness of 0.2-0.4 μm and length of 5-10 μm. Due to the hollows on the surface of the anode, one can assume that current channels with a size of about 1 μm form near the surface of metal in this corona discharge. Density of current in the channels increases due to compressing (pinching) of the current and the metal evaporates in interaction with the surface. As a result, the corona discharge near the anode surface can consist of numerous separate current channels.

Figure 4. Image of anode surface: a) view of surface near the anode tip, b) micropores on the anode surface

5. Research of the rotation of dielectric materials

Rotation of dielectrics in permanent electric field was first discovered in works [8,9]. Rotation of one of the electrodes or the dielectric cylinder improves the spatial uniformity of the corona discharge [4]. In this work the study was carried out using a dielectric cylindrical rotor. A unit with a rotor made of organic glass (Plexiglas) with a diameter of 4-6 cm, height of 2-4 cm, weight of 50-90 g was used to study the rotation motion. The axis of the rotor was made of steel (diameter 3 mm) and installed on friction bearings (the material is brass), which were fixed in the dielectric case. The electrodes: anode and cathode were made of wire 2-3 mm in diameter (material: copper, steel) and located at a distance of 1-2 mm from the rotor surface at a tangent to the surface. When high voltage is applied to the electrodes, starting from 10-12 kV, the rotor starts to rotate in the direction of the electrode installation.

Due to high voltage, a breakdown (voltage of breakdown is $E \approx 2$ kV/cm) may develop on the surface of the organic glass. The generated discharge in closest to the corona discharge in its parameters. The volt-ampere characteristics of this discharge represent a growing dependency. Current and voltage measurement errors are $\Delta I = \pm 1$ μA, $\Delta U = \pm 0.1$ kV. The dependence of rotor rotation frequency on voltage is shown in figure 5. The discharge starts at the minimal current of $I = 1 - 2$ μA. The discharge current is practically unchanged before the rotation frequency of $\nu = 20$ Hz. The rotation frequency measurement error is equal to $\Delta \nu = \pm 0.2$ Hz. Then, amperage suddenly changes for voltages $U = 15.5 - 17.5$ kV. Dependence of the rotation frequency on voltage has constant sections. The direction of the rotor rotation in these experiments was chosen to be counter-clockwise. The power
characteristics occurring during rotation were received as the rotor slowed down. The maximum value of the torque is as follows: $M_{\text{max}} \approx 9.2 \cdot 10^{-5} \text{ N}\cdot\text{m}$.

Rotation of the dielectric creates a near-surface layer of air making circular motions and drawing the corona discharge. The corona discharge area in this case increases and its spatial uniformity increases.

![Figure 5. Dependence of the rotation frequency of the rotor on voltage](image)

6. Conclusion
Properties of the corona discharge using a conic electrode were researched in the work. The discharge is characterized by two modes depending on amperage. The first mode at lower current is closer to the classic corona discharge. This discharge, which we have studied, is characterized by occurrence of electric oscillations within the range of 4 kHz-110 MHz. The possibility of plasma waves occurring in the near-electrode plasma with a thickness of 1 mm around the cathode was considered. Along with that, the plasmon waves, specific for the solid, may appear in the 1-50 μm thin superficial layer of the cathode metal. Microstructures form on the surface of the cathode as a result of the corona discharge effect. This can be connected with formation of discharge microchannels. Discrete values of dielectric rotation speed were found when testing the rotation properties of the dielectrics in presence of the corona discharge.

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