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STUDY OF ELECTRODYNAMICS' CHARACTERISTICS OF GAS DISCHARGE IN A NEEDLE-PLANE SYSTEM WITH ONE LIQUID ELECTRODE

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Researches were conducted on the electrodynamics' characteristics of gas discharge in a needle-plane electrode system with one liquid electrode under the application of high voltage of two types: unipolar negative pulse and combined (sum of DC and high-frequency AC high voltage) ones. This is necessary in many applications, particularly for water purification. Metal needle electrodes made of stainless steel were used, some of which were subjected to various treatments (polishing, coating with zinc nitride, titanium nitride or titanium oxide). It was shown that applying combined high voltage in the electrode system with a nitride coating results in a mean current 2 times smaller. When using a unipolar negative high-voltage pulse, the maximum mean discharge current was obtained with the untreated electrode system. This is due to the presence of a greater number of micro-protrusions on the needle electrodes, which leads to increased electric field intensity in the generation zone.

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INTRODUCTION

According to the World Health Organization, up to 80% of all diseases are transmitted through water, leading to the death of 25 million people annually worldwide [1]. Moreover, water can contain 13,000 toxic substances. As the global population grows, the problem of shortage of fresh water intensifies in many regions. Unfortunately, this problem is becoming increasingly urgent for Ukraine, despite the population decline and the shutdown of many environmentally hazardous enterprises.

Since drinking water purification is becoming a global problem, the development of innovative advanced oxidation processes for water purification remains a serious challenge. Traditional water purification methods using mechanical filters and chlorine are cumbersome and require significant maintenance costs. The use of reverse osmosis technology disrupts the mineral composition of water, as all salts and minerals are retained in the membrane. Moreover, this technology is highly sensitive to the quality of incoming water and cannot purify water from chlorine, only reducing its concentration.

Currently, water purification systems using ozone technology, which has a biocidal effect, are gaining popularity. This technology not only effectively disinfects water but also removes organic and inorganic pollutants that are toxic to humans. However, despite all its advantages, the ozonation method has several drawbacks. Ozone is insufficiently effective in breaking down phenolic compounds and disinfecting water from spores of pathogenic fungi, cysts of unicellular organisms, and certain types of viruses. Since the cost of ozonation processes is higher than that of chlorination processes, the search for new water purification methods to mitigate the shortcomings of ozone treatment, which could replace or complement existing methods, is an urgent task.

There are studies aimed at reducing the cost of ozonation processes by improving ozone generation efficiency, for example, by including a catalytic packing in the ozone generator, better dissolving ozone in water, and faster conversion of dissolved ozone into free radicals. Specifically, methods of electrolysis with pulsed corona discharge, dielectric barrier discharge, and contact glow discharge are being investigated for water purification [2]. The generation of ozone using a pulsed positive corona discharge generated in the gas phase between a flat high-voltage electrode made of vitreous carbon mesh and the water surface with an immersed polished stainless steel plate electrode was studied. The production of ozone was significantly influenced by the presence of water vapor formed during the evaporation of water at the gas-liquid interface under the influence of gas discharge, which led to increased energy efficiency in ozone production [3]. The work [4] describes the physical characteristics of the discharge on the water surface. The discharge was created using a needle-plane geometry on the water surface. In this case, positive voltage pulses were applied to the needle electrode. Installations based on electrical discharges in water or near the water surface are being tested at industrial water treatment facilities, so water purification by direct electrical discharges on the water surface can complement the ozone purification method.

Negative corona discharge is widely used in plasma-chemical methods, particularly in plasma-chemical reactions. To intensify the required reactions, it is advisable to use a negative corona in the pulsed Trichel mode at a relatively high voltage. When the voltage in the discharge gap increases, the discharge transitions to a diffuse stage. The diffuse stage is characterized by a constant current through the discharge gap and a low gas temperature in the discharge [5]. Therefore, before conducting experiments to study the biocidal properties of corona discharge, detailed experimental studies of the electrodynamic and optical characteristics of the discharge were carried out to optimize the discharge burning mode. In low-temperature plasma, when the average electron energy is an order of magnitude higher than thermal energy due to the excitation of vibrational levels of molecules, it is possible to increase the rate of chemical reactions. This significantly reduces energy consumption for the production of the final product of the reaction. Also, by optimizing the discharge burning mode, it is possible to prevent the discharge from transitioning into a spark. Considering this, it was shown that there are two characteristic regions of current-voltage characteristics corresponding to two different modes of discharge burning, which differ in the mechanisms of charged particle generation and their dynamics in the discharge gap. First, the current-voltage characteristics are realized by the Trichel current pulse, which exists until the discharge transitions to the diffuse burning stage. It has been established that the current-voltage characteristics of the discharge are well described by the Townsend formula [6].

Pilot studies were conducted to determine the biocidal effects of ozone and plasma-chemical discharge on the infectious rhinotracheitis virus, the reference strain of Escherichia coli, atypical Mycobacterium phlei, and the museum strain of Aspergillus flavus, all introduced into water. The results of plasma-chemical treatment show significant effectiveness of both methods against viruses and bacteria [7].

However, this effect requires further research for industrial implementation. Experimental studies were conducted on the electrodynamic characteristics of corona discharge with a liquid electrode under combined and pulsed high-voltage power with different coatings of needle-like electrodes with nitrides and metal oxides. Combined high-voltage power is the sum of DC and high-frequency AC high voltage, with the DC voltage being lower than the ignition voltage of the discharge.

1. EXPERIMENTAL STUDIES

The research was conducted on a specially designed and manufactured experimental setup, in which the gas discharge is ignited directly above the surface of the water, i.e., the water serves as a liquid anode. Fig. 1 shows the structural diagram of the experimental setup, which includes a high-voltage power supply, a discharge cell, and a system for measuring the electrodynamic characteristics of the discharge. Two high-voltage systems were used as the power supply. The first system generates a sinusoidal quasi-pulse high voltage. The second system produces a negative polarity pulse voltage with a duration of about 1 μs.

The discharge cell represents a needle-plane system, where the cathode is made in the shape of a "star" with a thickness of 0.1 mm, a diameter of 29 mm, and 31 "rays" made of stainless steel. The "rays" are bent at a 90-degree angle to the plane of the "star." Some stars have been additionally processed and coated (with a polished surface, zinc nitride spray, titanium nitride, or titanium oxide). The anode is a grounded metal container filled with tap water. The gap between the anode and cathode varies in the range of 4…6 mm. Calibrated current shunts with a nominal resistance of 50 Ω were used to measure the amplitude-time characteristics of the current pulses. The signal from the current shunts was recorded using a Tektronix TDS2024B digital oscilloscope. The high-voltage pulse voltage was measured with a Tektronix P6015A voltage divider with a bandwidth of 200 MHz. The average discharge current was measured using a microammeter. The working gas was injected into the discharge chamber using an AirPump membrane compressor. The air flow rate was measured with a rotameter and was 2 l/min.

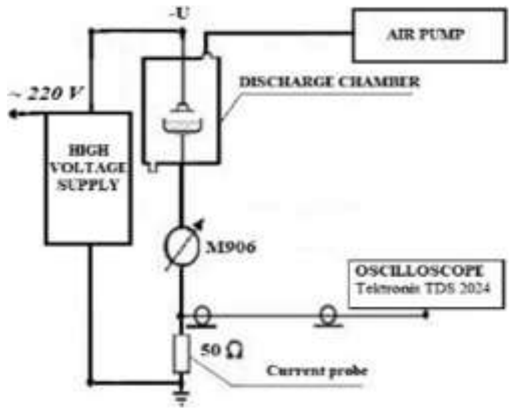

Fig. 1. Experimental setup

Fig. 2 shows the diagram of the formation of high-voltage negative polarity pulses with a regulated voltage pulse amplitude of 0…12 kV and a pulse repetition frequency of 0…15 kHz.

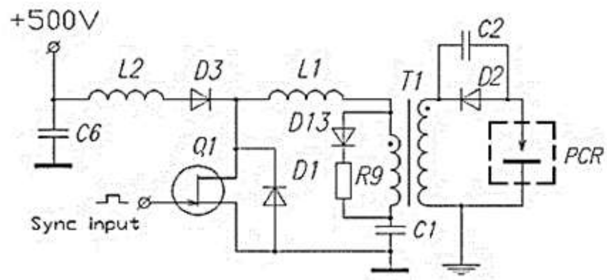

Fig. 2. Scheme of high-voltage pulse formation in a pulse power supply

2. RESULTS OF THE STUDY

Research on the electrodynamic characteristics of a gas discharge in a needle-plane system with a single liquid electrode was conducted under the application of two types of high voltage to the discharge gap. The first cycle of experiments was carried out with the application of a combined voltage, the form of which is shown in the upper trace of the oscilloscope (Fig. 3). The lower trace of the oscilloscope displays the total current, which consists of the charging current of the electrode system and the discharge current that corresponds to the ignition of discharge in the discharge gap. When studying the current-voltage characteristics of the discharge, only the discharge component of the total current was measured, represented on the oscilloscope as a distortion of the total current.

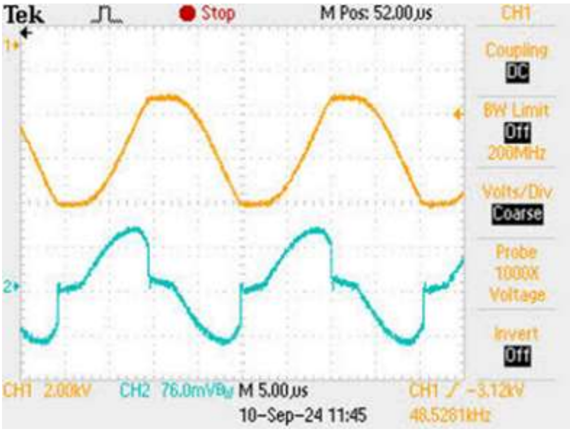

Fig. 3. Oscillograms of combined voltage (upper) and total current (bottom)

Fig. 4 shows the current-voltage characteristics of a gas discharge in a needle-plane system with one liquid electrode at an interelectrode gap of 4 mm.

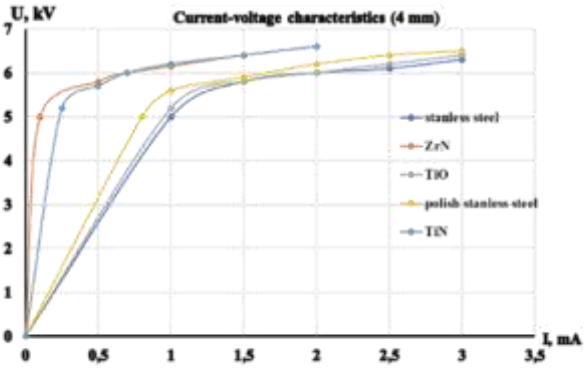

Fig. 4. Current-voltage ampere characteristics of the discharge when using a supply of combined voltage with a gap of 4 mm between the cathode and anode

The graphs show that to achieve the same average current, higher voltage needs to be applied to needle-like electrodes coated with metal nitrides, which leads to greater power being invested in the discharge. This may be due to the increased resistance of the nitride layer and, consequently, a lower secondary ionization coefficient. However, in the electrode system with nitride-coated needle-like electrodes, a significantly lower (by a factor of 2) average current is achieved before the discharge transitions to the spark stage.

Fig. 5 shows the current-voltage characteristics of the discharge in the Trichel mode for a needle-plane electrode system with one liquid electrode, with an inter-electrode gap of 6 mm.

The graphs show that as the inter-electrode gap increases, the differences in the electrodynamic characteristics of the discharge in electrode systems with different coatings on the needle-like electrodes become less significant. This is due to the increase in the drift zone of the discharge gap, which leads to a redistribution between displacement current and conduction current in the total current.

The second cycle of experiments was conducted using a pulsed high voltage power supply that generates unipolar negative pulses. Characteristic oscillograms of voltage (upper trace) and total current (lower trace), which consists of the charge current of the electrode system and the discharge current, are shown in Fig. 6.

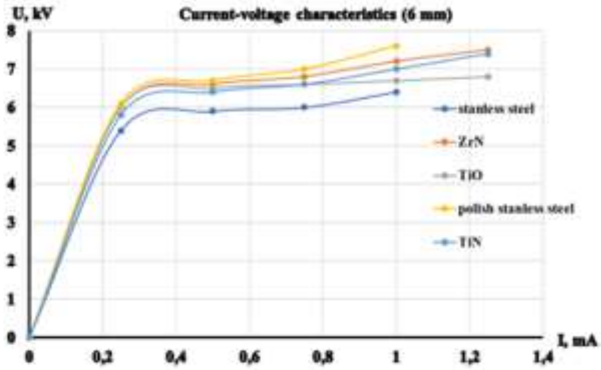

Fig. 5. Current-voltage characteristics of the discharge using a supply of combined voltage with a gap of 6 mm between the cathode and anode

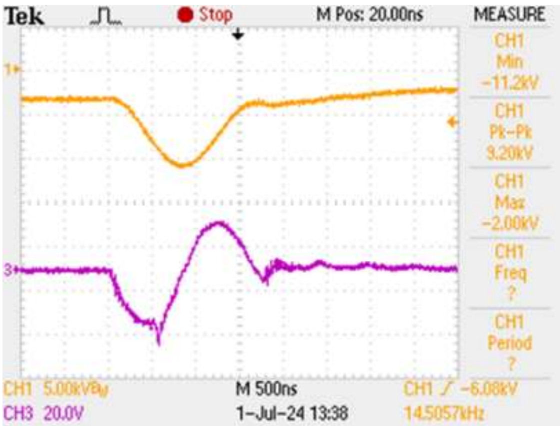

Fig. 6. Oscillograms of unipolar negative pulse combined voltage (upper) and total current (bottom)

Fig. 7 presents characteristic oscillograms of the voltage across the discharge gap as the amplitude of high-voltage pulses changes from 8.5 to 9.6 kV, with a pulse repetition frequency of 12 kHz.

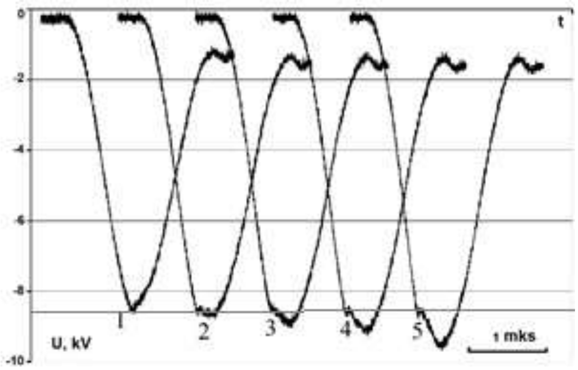

Fig. 7. Oscillograms of the voltage at the discharge gap at different pulse amplitudes

The provided oscillograms clearly fix the moment of discharge breakdown. It is evident that the breakdown voltage of the discharge depends little on the amplitude of the applied high-voltage pulse and is 8.5 kV for an interelectrode gap of 4 mm.

Fig. 8 shows the current-voltage characteristics of the gas discharge when applying high-voltage negative polarity pulses in the needle-plane electrode system with one liquid electrode. The gap size was 4 mm. The pulse repetition frequency was 5 and 15 kHz.

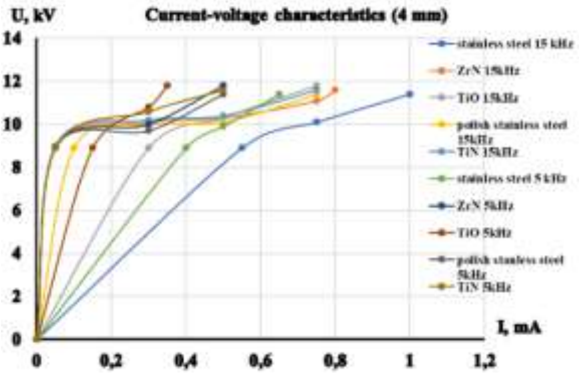

Fig. 8. Current-voltage characteristics of corona discharge using a pulse power source with a pulse repetition frequency of 5 and 15 kHz at a gap between the cathode and anode of 4 mm

Fig. 9 shows the current-voltage characteristics of the gas discharge with one liquid electrode at a gap of 6 mm and a high-voltage pulse repetition frequency of 5 and 15 kHz.

From the provided graphs, it can be concluded that the transition from the diffuse discharge stage to the spark stage, when a high-voltage pulse is applied to the discharge gap, occurs at the same applied voltage, regardless of the gap size and the type of coating on the needle electrodes. At the same time, the maximum average discharge current was obtained with untreated metallic electrodes. This may be due to the presence of more microprotrusions on the needle electrodes, leading to a higher electric field intensity in the generation zone and, consequently, a higher pulse current in the discharge, regardless of the pulse repetition frequency.

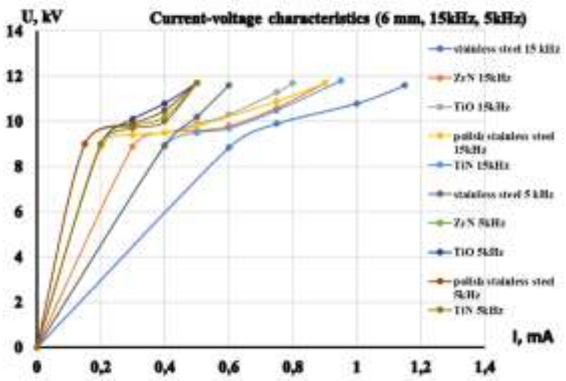

Fig. 9. Current-voltage characteristics of corona discharge using a pulse power source with a pulse repetition frequency of 5 and 15 kHz at a gap between the cathode and anode of 6 mm

CONCLUSIONS

Research has been conducted on the electrodynamics of a gas discharge in an electrode system with a needle-plane configuration and one liquid electrode. Stainless steel needle electrodes were used, some of which were subjected to various treatments (polished stainless steel, zinc nitride coating, titanium nitride, and titanium oxide). To study the voltage-current characteristics, high-voltage was applied to the gas gap, with two types of voltage used: a combined voltage consisting of a DC and a high-frequency component, and a unipolar negative pulse voltage.

When applying combined high voltage to the discharge gap to achieve the same average current, higher voltage must be applied to the needle electrodes coated with metal nitrides. This results in the need to use more power for the discharge. This is due to the increased resistance of the nitride layer and, consequently, a lower secondary ionization coefficient. However, in the electrode system with nitride-coated needle electrodes, a significantly lower (by a factor of 2) average current is achieved before the discharge transitions to the spark stage.

As the interelectrode gap increases in the same electrode system with the same type of high-voltage supply, the drift zone expands, resulting in a redistribution between displacement current and conductivity current within the total current. This neutralizes the differences in the electrodynamic characteristics of the discharge in the electrode system with different coatings on the needle electrodes.

When using a unipolar pulse high-voltage supply, the maximum average discharge current was observed in the electrode system without treatment. This is due to the presence of a greater number of microprotrusions on the needle electrodes, which leads to higher electric field intensity in the generation zone and, accordingly, a higher pulse current in the discharge, regardless of the pulse repetition frequency.

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ДОСЛІДЖЕННЯ ЕЛЕКТРОДИНАМІЧНИХ ХАРАКТЕРИСТИК ГАЗОВОГО РОЗРЯДУ В СИСТЕМІ ГОЛКА-ПЛОЩИНА З ОДНИМ РІДКИМ ЕЛЕКТРОДОМ

І.М. Оніщенко, Г.В Таран, О.О. Замурієв, П.О. Опалєв

Проведено дослідження електродинамічних характеристик газового розряду в електродній системі голка-площина з одним рідким електродом при прикладанні негативної високої напруги двох видів: імпульсної та комбінованої (однополярної постійної + двохполярної змінної). Цей тип розряду використовується у багатьох плазмохімічних процесах, зокрема, для очистки та знезараження води. Використовувались металеві голчасті електроди з нержавіючої сталі, деякі з яких пройшли різну обробку (полірування, покриття нітридом цинку, нітридом титану, оксидом титану). Показано, що комбінована висока напруга в системі електродів з нітридним покриттям призводить до вдвічі меншого середнього струму. При використанні уніполярного імпульсу високої напруги максимальний середній струм розряду отримано з необробленою електродною системою. Це пов'язано з наявністю більшої кількості мікровиступів на голчастих електродах, що призводить до збільшеної напруженості електричного поля в зоні генерації.