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STUDY OF THE IGNITION VOLTAGE OF A NEGATIVE PULSED CORONA DISCHARGE IN OXYGEN WITH COMBINED POWER SUPPLY

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The study investigates the ignition of a negative pulsed corona discharge in oxygen in plasma-chemical reactors with a multi-pin segmented cathode. The dependence of the ignition voltage on the amplitude of the low-voltage DC applied in intervals between high-voltage pulses is presented. It is shown that under all investigated experimental conditions, the ignition voltage U_i decreases monotonically with the growth of U_{dc}/d. It is also demonstrated that electrode shielding leads to an increase in ignition voltage.

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INTRODUCTION

The study of negative pulsed corona discharge in oxygen is of interest because this gas discharge can be used as an alternative to barrier discharge for high-efficiency ozone synthesis [1]. The main challenge in increasing the efficiency of ozone generators operating on pulsed corona discharge is to increase the power density applied per unit area of the working surface of the plasma-chemical reactor's anode. One possible approach to increasing the power density is by raising the repetition rate voltage pulses. However, experimental research shows [2] that as the pulse repetition rate increases, the transition voltage from negative corona to spark discharge decreases due to the accumulation of negative space charge in the discharge gap. Therefore, it is necessary to find conditions for a spark-free discharge mode when the amplitude and frequency of high-voltage pulses increase.

To prevent spark breakdown at increased frequencies and amplitudes of high-voltage pulses, a combined power supply was proposed for the plasma-chemical reactor, i.e., a sequence of high-voltage pulses overlaid on a low-voltage DC of the same polarity [3]. In this case, the external electric field existing in the discharge gap during the intervals between high-voltage pulses promotes the accelerated drift of negative space charge toward the anode, reducing the voltage required for the next high-voltage pulse to ignite the discharge. Changes in the ignition voltage can serve as an indicator of changes in the amount of accumulated space charge in the discharge gap [4]. The goal of this work is to study the ignition of a negative pulsed corona discharge in air enriched with oxygen (O_2 ~ 93%) depending on the amplitude of the low-voltage DC and the geometric parameters of the segmented cathode electrode system.

1. EXPERIMENTAL SETUP

The plasma-chemical reactor consisted of a coaxial system with a cylindrical anode made of thin-walled stainless steel tubing with an internal insert of TMG-F/A1 graphite foil, 0.35 mm thick. The inner diameter of the anode was 38 mm, and the length was 500 mm. Along the anode axis, using a high-voltage insulator, a segmented cathode was placed, consisting of cathode sections mounted on a rod at a distance l from each other Fig. 1.

Fig. 1. Photo of the cathode.

Each cathode section was a 0.5 mm thick stainless steel disk with 25 radially arranged individual cathodes Fig. 2.

Fig. 2. Cathode section

Each individual cathode had a height of 3 mm and a rectangular cross-section of 0.5x0.5 mm. The allowable deviation of the segmented cathode axis from the cylindrical anode axis was no more than 50 µm. The inter-electrode gap d was 3.5, 4, 4.5, 5, and 5.5 mm. The distance between the cathode sections l was 4, 6, 8, and 10 mm. The reactor length remained constant, i.e., the total number of cathode sections changed. Depending on the inter-electrode gap and the distance between the cathode sections, the electrical capacitance of the plasma-chemical reactor varied between 55 and 85 pF. It should be noted that the uniformity of all individual cathodes is crucial for the synchronous ignition of the plasma-chemical reactor as a whole. Therefore, special attention was paid to the processing and calibration of the cathode sections.

Fig. 3 shows a flowchart of the experimental setup. Experiments were conducted on a module consisting of three plasma-chemical reactors connected in series for gas flow and in parallel for electrical power. To match the high-voltage pulse generator, the total capacitance of the three plasma-chemical reactors did not exceed 250 pF. The power source was a high-voltage pulse generator with the following parameters: the amplitude of high-voltage pulses on a capacitive-resistive load was adjustable between 5…15 kV, the pulse duration at half-maximum was ~1 µs, and the pulse repetition frequency was 1…20 kHz, with a power of 150 W. For the plasma-chemical reactors, a combined power supply was used, so along with the pulsed high-voltage power source, a low-voltage DC source with adjustable voltage in the range of 0 to 1 kV was employed.

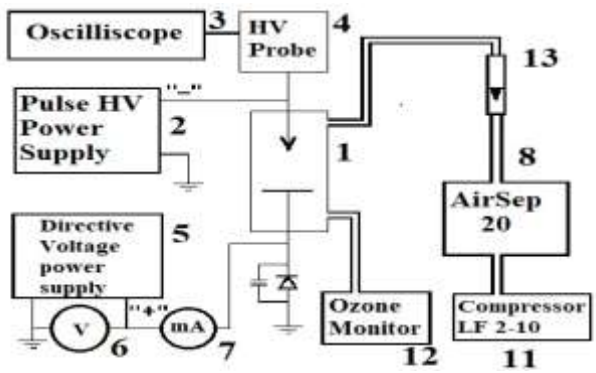

Fig. 3. Schematic of the experimental setup.
1 – Plasma-chemical reactor module; 2 – High-voltage pulse generator; 3 – Tektronix TDS 2024 oscilloscope; 4 – Tektronix P6015A high-voltage divider; 5 – DC voltage source; 6 – M42101 voltmeter; 7 – M42301 milliammeter; 8 – AirSep-20 oxygen generator; 11 – Atlas Copco LF 2-10 air compressor; 12 – Teledyne Instruments 454-H ozone analyzer; 13 – RM-4G rotameter, Oxygen Analyzer PMA 10

The gas mixture enriched with oxygen was supplied by an AirSep20 oxygen generator, with air delivered from an oil-free Atlas Copco LF 2-10 compressor with a capacity of 3.1 L/s at 10 bar pressure. The flow rate of the oxygen-enriched gas mixture was controlled by an RM-4G rotameter and was 0.5…1.0 Nm³/h. Given that the total volume of the plasma-chemical reactors is about 2 L, such a gas flow rate prevented the accumulation of plasma-chemical reaction products in the reactors, which significantly affect the electrodynamic discharge parameters. The oxygen concentration in the enriched air mixture was monitored by an Oxygen Analyzer PMA 10 and was 93…95%. The ozone concentration at the module outlet was measured by a Teledyne Instruments 454H ozone analyzer with a concentration range of 0…200 g/m³. To record the temporal and amplitude characteristics of the voltage pulse, a Tektronix P6015A high-voltage voltage divider with a bandwidth of 75 MHz was used, and the signal was fed into a Tektronix TDS 2024B digital oscilloscope (sampling rate 1 GHz, oscilloscope bandwidth 200 MHz). DC voltage was monitored by a M42101 voltmeter, and current through the DC source was measured by a M42301 milliammeter. The experimental setup is schematically presented in Fig. 3.

2. EXPERIMENTAL RESULTS

During the experiments, oscillograms of voltage pulses on the plasma-chemical reactor module were recorded under various experimental conditions. The shape of the formed high-voltage pulse on a capacitive load is close to a half-wave of a sine. Since the plasma-chemical reactor module represents a capacitive-resistive load with time-varying characteristics, at the moment of discharge ignition, it is purely capacitive, and after ignition, it becomes capacitive-resistive. After ignition, the resistance of the discharge gap begins to decrease and reaches a finite value, while the capacitance, due to the capacitance of the newly formed conductive region in the discharge gap, increases. The greater the change in the load's electrical parameters, the more the shape of the voltage pulse is distorted. These changes in the shape of the recorded voltage pulse easily allow for identifying the moment of discharge ignition and determining the ignition voltage value.

Characteristic voltage pulse oscillograms on the plasma-chemical reactor module for high-voltage pulse amplitudes from 8.5 to 9.6 kV, pulse repetition rate 12 kHz, constant voltage 300 V, inter-electrode gap d = 5.5 mm, and distance between cathode sections l = 8 mm are shown in Fig. 4.

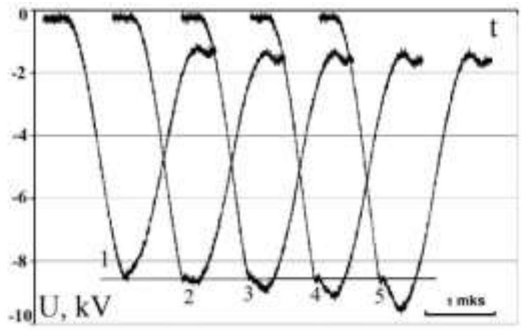

Fig. 4. Oscillograms of voltage pulses with amplitudes:
1 – 8.5; 2 – 8.7; 3 – 8.95; 4 – 9.15, and 5 – 9.6 kV

The moment of ignition is clearly traceable on the oscillograms. It is evident that the ignition voltage U_i is practically independent of the amplitude of the applied high-voltage pulse and equals U_i = 8.5 kV for these experimental conditions.

Next, we consider the effect of low-voltage DC applied during the intervals between high-voltage pulses on the ignition voltage of a negative pulsed corona discharge in oxygen with varying geometric parameters of the electrode system. To this end, we introduce the average electric field strength across the gap during the intervals between high-voltage pulses U_{dc} /d, where U_{dc} is the DC voltage and d is the length of the discharge gap.

The given dependence (Fig. 5) illustrates the relationship characteristic of all electrode system configurations between U_i and the distance between the cathode sections, *l*. The distance between the cathode sections, *l*, affects the degree of shielding of the cathodes from each other, which is manifested in the change in the distribution of the electric field strength in the immediate vicinity of the ionization region surrounding the cathode. The curves in Fig. 5 show that for electrode systems where the distance between the cathodes is less than or equal to the inter-electrode distance, $l \leq$ d, the ignition voltage significantly exceeds the ignition voltage for electrode systems with $l >$ d. Another feature is the monotonic decrease in the ignition voltage with increasing U_{dc}/d. The nature of the dependence is close to linear for the investigated range of U_{dc} /d = 0…600 V/cm. It can be seen that for different distances l between the cathode sections, the curves run almost parallel, which means that the inhomogeneity of the electric field strength distribution at the cathode, determined by the geometric parameters of the electrode system, although it affects Ui, does not affect the magnitude of the change in ignition voltage U_i.

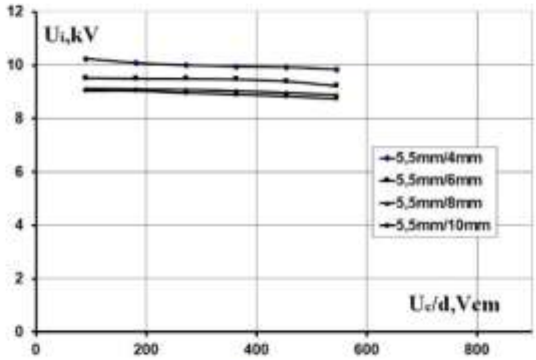

Fig. 5. The dependence of the ignition voltage U_i on U_{dc}/d in the electrode system with an inter-electrode gap d = 5.5 mm and cathode section distances l = 4, 6, 8, 10 mm

For a more detailed examination of the behavior of U_i depending on the average electric field strength across the discharge gap, we compare the ignition voltage in electrode systems with a similar distribution of the electric field strength at the cathode, i.e., with the same distance between cathode sections l, but for different inter-electrode gaps d.

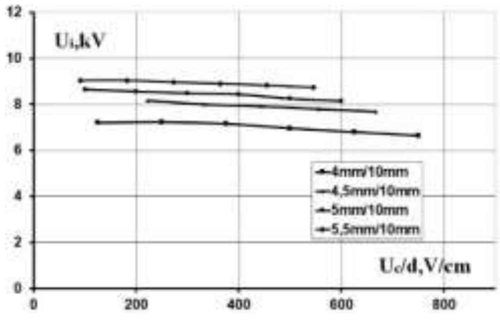

Fig. 6. Dependence of the ignition voltage U_i on U_{dc}/d in an electrode system with a distance between cathode sections of l = 10 mm and an inter-electrode gap of d = 4.0, 4.5, 5.0, 5.5 mm

The curves presented in Fig. 6 show a strong dependence of U_i on the magnitude of the discharge gap. The shape of the curves in Fig. 6 is similar to that in Fig. 5. All experiments were conducted at the same high-voltage pulse repetition frequency of 12 kHz, which provides a time between high-voltage pulses of 83 µs. During the time between pulses, given a specific electric field strength, the distance can be estimated over which the bulk negative charge will drift in the electric field according to $v = \mu \cdot E$, where µ is the mobility of negative ions, 2.2 cm²/V/s, and E is the electric field strength in V/cm. In the considered range of electric field strength, during the time between pulses, 90.9…857 V/cm, the bulk charge will shift over a distance of 0.0167…0.157 cm, respectively.

Figs. 7-9 present the dependencies of the relative change in ignition voltage U_i/U_0, where U_0 is the value of U_i at U_{dc} = 100 V, on the distance L over which the bulk charge moves away from the cathode as a result of drift. The normalization of U_i is carried out to highlight changes in U_i associated with the characteristics of the electric field strength distribution at the cathode, without considering the dependence of the absolute magnitude of U_i on d.

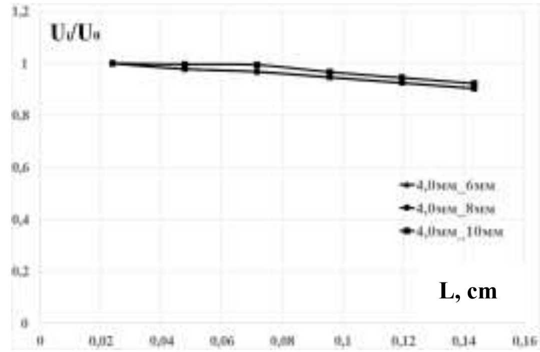

Fig. 7. Dependence of the normalized ignition voltage U_i/U_0 on L in an electrode system with distances between cathode sections l = 6, 8, 10 mm, and an inter-electrode gap of d = 4.0 mm, on L

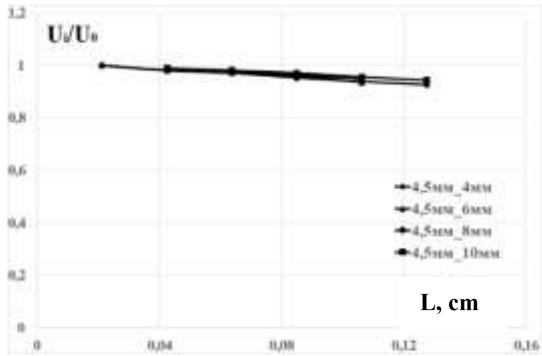

Fig. 8. Dependence of the normalized ignition voltage U_i/U_0 on L in an electrode system with distances between cathode sections l = 4, 6, 8, 10 mm, and an inter-electrode gap of d = 4.5 mm

DISCUSSION OF EXPERIMENTAL RESULTS

The ignition voltage is the value at which the electric field strength in the vicinity of the cathode becomes sufficient for electrical breakdown of the gas. This field strength is the sum of the field strength created by the potential difference applied to the electrode system and the field strength created by the bulk charge accumulated in the discharge gap. Thus, a change in ignition voltage indicates a change in the magnitude of the bulk negative charge. According to the conducted assessment, the distance over which the bulk charge will move during the time between pulses is 0.0167…0.157 cm. The generation zone at the coronating surface of the cathode is about 100 µm in length.

Therefore, the influence of the bulk charge on the generation zone is limited. The curves presented in Figs. 7-10 confirm that the relative change in ignition voltage U_i/U_0 depending on L does not depend on the distance between the cathode sections, which determines the distribution of the electric field strength at the cathode.

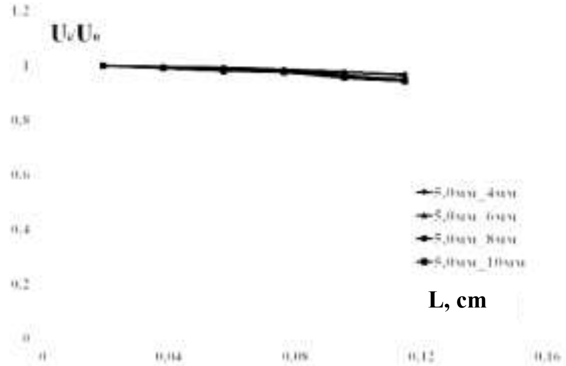

Fig. 9. Dependence of the normalized ignition voltage U_i/U_0 on L in an electrode system with distances between cathode sections l = 4, 6, 8, 10 mm, and an inter-electrode gap of d = 5.0 mm on L.

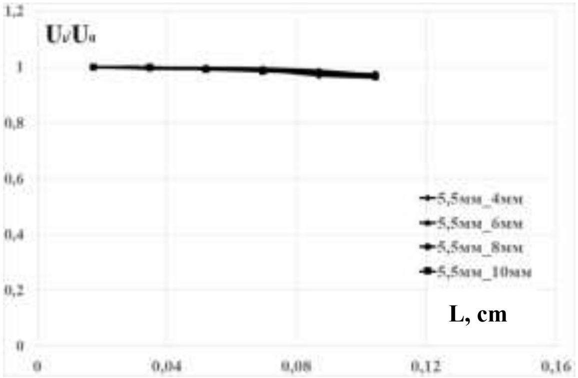

Fig. 10. Dependence of the normalized ignition voltage U_i/U_0 on L in an electrode system with distances between cathode sections l = 4, 6, 8, 10 mm, and an inter-electrode gap of d = 5.5 mm on L

From the graphs, it is evident that the relative change in ignition voltage with changes in U_{dc}/d in electrode systems with a similar distribution of the electric field strength at the cathode, with a fixed value of l, is the same.

CONCLUSIONS

This study investigated the dependencies of the ignition voltage of a negative pulsed corona discharge in air enriched with oxygen (O_2 ~ 93%) in plasma chemical reactors with a segmented cathode, depending on the average electric field strength across the discharge gap U_{dc}/d in the range of 90…900 V/cm, applied in intervals between high-voltage pulses, at a high-voltage pulse repetition frequency of 12 kHz. It was shown that under all experimental conditions studied, there is a monotonic decrease in ignition voltage U_i with increasing U_{dc}/d. It was hypothesized that this discharge behavior is due to the drift of the bulk charge under the influence of low-voltage DC voltage applied to the discharge gap between high-voltage pulses.

It was shown that the shielding of the electrodes from each other leads to an increase in ignition voltage. For electrode systems where the distance between the cathodes is less than or equal to the inter-electrode distance $l \leq$ d, the ignition voltage significantly exceeds that for electrode systems with l > d.

For each investigated value of the discharge gap d, the relative change in ignition voltage is the same for all values of the distance between cathode sections. This allows concluding that the influence of the bulk charge accumulated in the discharge gap on the generation zone is limited.

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ДОСЛІДЖЕННЯ НАПРУГИ ЗАПАЛЮВАННЯ НЕГАТИВНОЇ ІМПУЛЬСНОЇ КОРОНИ У КИСНІ ПРИ КОМБІНОВАНОМУ ЖИВЛЕННІ

Б.Б. Кадолін, Г.В. Таран, Л.М. Завада, М.О. Єгоров

Досліджено запалювання негативного імпульсного коронного розряду в кисні у плазмохімічних реакторах з сегментованим катодом. Наведено залежність напруги запалювання від амплітуди низьковольтного постійного струму, що подається в проміжках між імпульсами високої напруги. Показано, що за всіх досліджених умов експерименту напруга запалювання U_i монотонно зменшується зі зростанням U_{dc}/d. Також показано, що екранування електродів призводить до збільшення напруги запалювання.