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STUDY OF THE PULSED NEGATIVE CORONA IN OXYGEN IN AN ELECTRODE SYSTEM WITH A MOVING CATHODE

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A study of the pulsed negative corona in oxygen at the combined power supply in the electrode system with a moving cathode, its electrodynamic characteristics, and the amount of synthesized ozone, depending on the cathode movement speed, was carried out. It is shown that when the threshold cathode motion speed of 6.98 m/s is exceeded, an increase in the maximum possible amplitude of the high-voltage pulse, the negative corona pulse current, and the amount of synthesized ozone is observed. At a cathode velocity of 22.77 m/s, the amplitude of the high-voltage pulse increases by 1.15 kV relative to the stationary cathode, the pulse current and the amount of synthesized ozone doubled.

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INTRODUCTION

The negative corona in oxygen is an effective source of ozone. Therefore, it is important to search for discharge conditions when ozone synthesis is most efficient. The most promising is the pulsed negative corona, the current of which is a sequence of the so-called first pulses of the Trichel sequence. When a high voltage is applied to the electrode system, a sequence of current pulses is formed, the first of which has an amplitude significantly higher than the amplitude of the subsequent pulses [1].

Fig. 1 shows the voltage and discharge current waveform of the negative corona in the Trichel pulse mode.

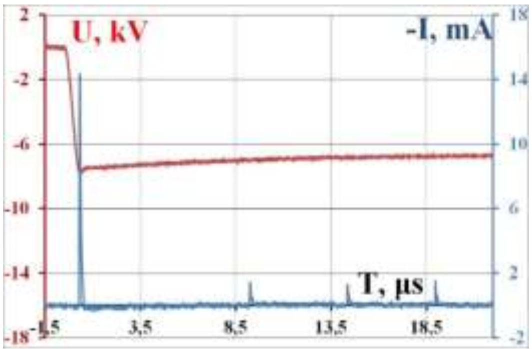

Fig. 1. Oscillogram of the negative corona strain in the mode of Trichel pulses

The development of the first Trichel pulse involves the movement of an ionization wave that starts at a certain distance from the cathode in the direction of the cathode (similar to the movement of a streamer in a positive-polarity corona discharge) [2]. The first Trichel pulse differs from regular current pulses by the increased electric field intensity during the movement of the ionization wave. Therefore, during the development of the first Trichel pulse, the dissociation of oxygen molecules in the process of impact dissociation is much more efficient than in regular Trichel pulses due to the greater number of electrons with energy exceeding the threshold (≥10 eV).

In order to increase the efficiency of barrier-free ozonators, it is proposed to use a pulsed high-voltage power supply with a pulse length that is much shorter than the Trichel pulse period. However, a negative charge consisting of negative ions accumulates in the discharge gap. In conditions when there is no voltage on the electrode system after the high voltage pulse, the negative charge drifts in the discharge gap to the electrodes under the influence of its own electric field and the field of image charges on the electrode surface. The time of such drift to the electrodes can be tens of ms. This imposes a significant limitation on the maximum pulse repetition rate of high-voltage pulses, provoking the transition of the negative corona to spark discharge. Therefore, their presence limits the maximum amplitude of high-voltage pulses. In order to accelerate the removal of negative ions from the discharge gap, a combined electrical power supply is used, which is a sequence of high-voltage pulses against a constant voltage. The use of a constant voltage of the same polarity with a value an order of magnitude smaller than the amplitude of the high-voltage pulse allows to increase the frequency of high-voltage pulses to ≈ 20 kHz [3].

Another means of removing accumulated negative ions can be high-speed (more than 10 m/s) pumping of gas through the discharge space. The high-speed movement of gas through the electrode system makes the gas flow turbulent. The vortex gas flow captures negative ions and carries them out of the discharge zone. In ozonators with a low flow rate of working gas, the creation of a high-speed flow is associated with a number of technical difficulties. However, a mechanism to reduce the impact of negative ions similar to high-speed gas flow can be realized by creating an electrode system with a moving cathode [4]. Shifting the cathode parallel to the anode away from the accumulation of negative ions will reduce their influence on the premature development of the spark, which will increase the amplitude of the high-voltage pulse without the risk of sparking.

This paper proposes a model of a barrier-free ozonator with a moving cathode. Changing the cathode rotation speed makes it possible to set the linear speed of individual cathodes relative to the anode. In the course of experimental studies, the electrodynamic characteristics of the negative corona in oxygen and the ozone concentration were measured as a function of the cathode rotation speed.

1. EXPERIMENTAL STAND

To conduct the experiment, an experimental stand was assembled. The testbed consists of two subsystems: a gas-dynamic one, which is schematically shown in Fig. 2, and the electrical one, which is schematically shown in Fig. 3. The gas-dynamic system includes a source of working gas enriched with oxygen up to 93 vol.%. (ONYX+), the moisture content of which corresponds to the dew point of -70°C. Also an oxygen concentration meter PMA-10. The ozone concentration was measured using a Teledyne Instruments 454H ozone analyzer with a measuring range of 0…200 g/m^3. The flow rate of the working gas was controlled by the RM 0.12 G device with a measuring range from 0.001 to 0.12 m^3 /h and was 2 l/min.

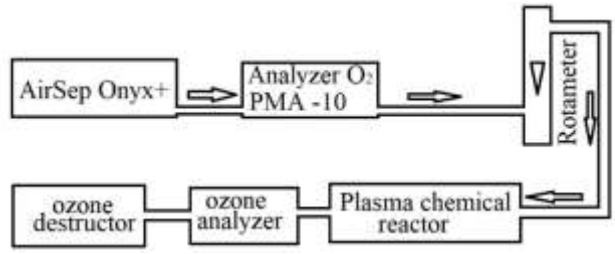

Fig. 2. Block diagram of the gas path

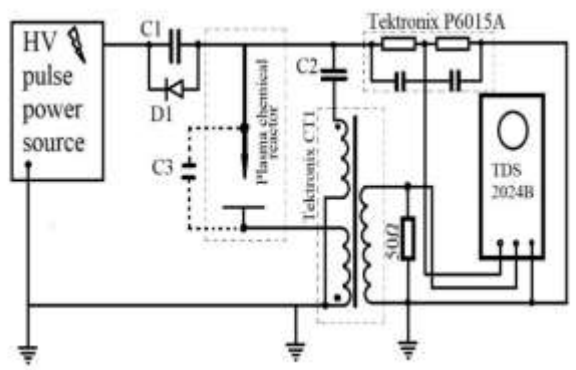

Fig. 3. Electrical circuit of the experimental stand

The electrical part consisted of a high voltage pulse source. The pulse frequency was 500…15 kHz, the amplitude was 6…12 kV, the pulse duration was 1.5 μs, and the four-channel oscilloscope was a TektronixTDS 2024B (sampling rate was 1 GHz, oscilloscope bandwidth was 200 MHz). A Tektronix P6015A high-voltage voltage divider with a bandwidth of 75 MHz was used to record the time and amplitude parameters of high-voltage pulses. To record the discharge current, a Tektronix CT-1 current shunt with a transformation ratio of 5 mV/1 mA and a bandwidth of 1 GHz was used. In the diagram, C1 = 570 pF is a capacitor of the DC voltage circuit, C2 = 54 pF is a capacitor that simulates the intrinsic electrical capacitance of the plasma chemical reactor, and C3 = 54 pF is the intrinsic electrical capacitance of the plasma chemical reactor.

The plasma reactor consists of a 500 mm long cylinder made of fine graphite with an internal diameter of 38 mm. A metal rod with a diameter of 8 mm is fixed along the cylinder axis. On the metal rod are fixed cathode sections (Fig. 4) in the amount of 57 pcs. The distance between the cathode sections was 8 mm. Each of the cathode sections has a diameter of 29 mm. The number of individual cathodes on the cathode section is 15 pcs. with a length of 5 mm and a cross section of 0.5x0.5 mm. The deviation of the rod axis from the cylinder axis does not exceed 20 μm.

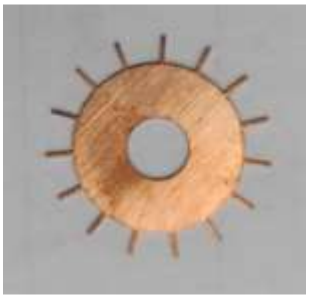

Fig. 4. The cathode section

Fig. 5 shows a photo of the central rod with cathode sections. The metal rod is fixed along the cylinder axis with high-voltage insulators. Ceramic bearings are mounted in the end surface of the insulators. A gear made of insulating material is mounted at one end of the rod, which transmits torque from an electric motor powered by a DC source to the rod. The speed of the electric motor was set by the supply voltage. The rod rotation speed in the experiment was 0, 1500 rpm (linear cathode velocity of 2.277 m/s), 3000 rpm (4.55 m/s), 4600 rpm (6.98 m/s), 6000 rpm (9.1 m/s), 9000 rpm (13.66 m/s), 12000 rpm (18.21 m/s), 15600 rpm (22.77 m/s).

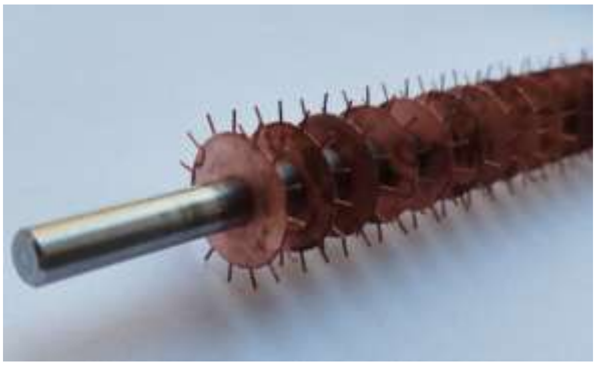

Fig. 5. Photo of the central rod with cathode sections

At the same time, during the rotation of the central rod, the cathodes move relative to the anode and the distance by which the cathode moves relative to the anode is at 1500 rpm – 0.152 mm, at 3000 mm – 0.304 mm, at 4600 rpm – 0.465 mm, at 6000 rpm – 0.607 mm, at 9000 rpm – 0.911 mm, at 12000 rpm – 1.214 mm, at 15000 rpm – 1.518 mm.

The rotational speed was monitored using a DT-2234C$^+$ laser tachometer with a measuring range of 2.5 - 99999 rpm with an accuracy of 0.05%. Fig. 6 shows a photo of the plasma chemical reactor.

Fig. 6. Photo of a plasma-chemical reactor with a rotating cathode driven by an electric motor

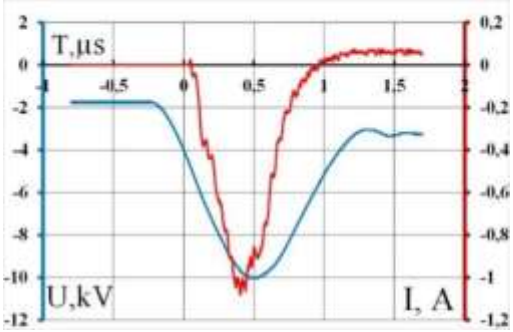

Fig. 7. A typical waveform of a discharge current pulse (red curve) and a high-voltage pulse (blue curve)

Measuring the current of a pulsed negative corona presents some difficulties. A plasma chemical reactor is a capacitively resistive load. Therefore, under pulsed power supply conditions, the total current in the electrical circuit is the sum of the charging current of the reactor's own electrical capacitance and the gas discharge current. To obtain the discharge current oscillograms, it is advisable to remove the charging current of the reactor's own capacitance from the total current in the reactor power circuit. This was done using a decoupling circuit. To do this, a high-voltage capacitor C2 was added to the electrical circuit, the value of which was equal to the value of the plasma chemical reactor's own capacitance.

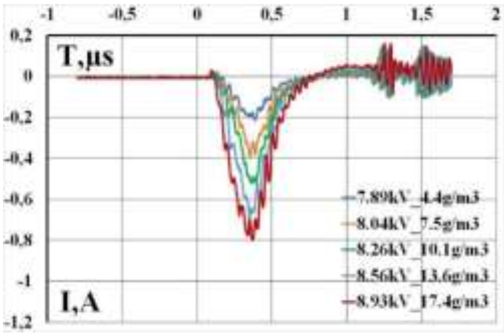

Fig. 8. Oscillograms of negative corona current pulses in oxygen without rotation of the central rod

The total current flowing through the reactor and the current of the added capacitor are oscilloscoped separately using a current shunt. The Tektronix CT1 current shunt is a measuring transformer. The primary winding of the measuring transformer is a current-carrying conductor. During the measurement, the primary windings were the conductor with the discharge current and the conductor with the charge current of the added capacitor C2, which were commuted in opposite directions. As a result, we have an oscillogram showing the gas discharge current. In Fig. 7. shows a typical waveform of a high voltage pulse and a negative corona current pulse in oxygen obtained during the experiment. The ozone concentration was also measured during the experiment.

All experiments were conducted at a frequency of high-voltage pulses of 15000 Hz. The level of the DC component of the supply voltage was 1.7 kV.

2. EXPERIMENTAL RESULTS

Further in the text show oscillograms of negative corona current pulses obtained from the plasma chemical reactor at a central rod rotation speed of 0 rpm (Fig. 8), 3000 rpm – linear velocity of cathodes 4.55 m/s (Fig. 9), 4600 rpm – 6.98 m/s (Fig. 10), 15600 rpm – 22.77 m/s (Fig. 11). For each oscillogram, the corresponding high-voltage pulse amplitude and ozone concentration synthesized under these discharge conditions are indicated.

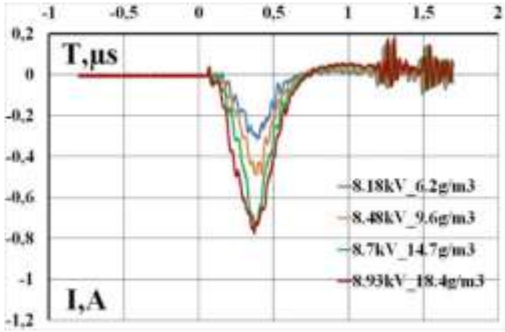

Fig. 9. Oscillograms of negative corona current pulses in a plasma-chemical reactor in oxygen at a central rod rotation speed of 3000 rpm

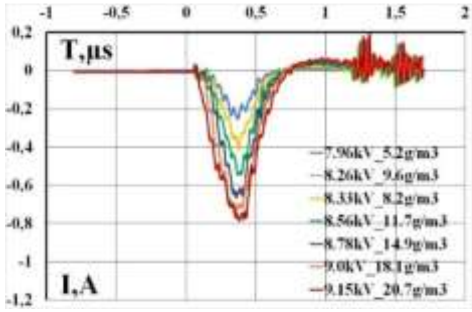

Fig. 10. Oscillograms of negative corona current pulses in a plasma-chemical reactor in oxygen at a central rod rotation speed of 4600 rpm

Comparative analysis of the above oscillograms shows that the central rod rotation speed up to 3000 rpm does not significantly change either the current characteristics of the negative corona or the ozone production capacity.

Starting from 4600 rpm, the amplitude of the high voltage pulses increases, which is the maximum possible for stable operation without the negative corona turning into a spark discharge. The amplitude of the discharge current pulses also increases accordingly when the center rod rotation speed exceeds 3000 rpm. Ozone synthesized in the discharge also increases. To compare the changes in the electrodynamic characteristics of the discharge, the negative corona pulse current and the power input to the discharge were calculated from the obtained oscillograms. The time interval from the beginning of the current pulse to the moment when the current changes direction was separated on the oscillogram (Fig. 12). Within this time interval, the charge transferred during one current pulse was calculated, as well as the energy released during the current pulse.

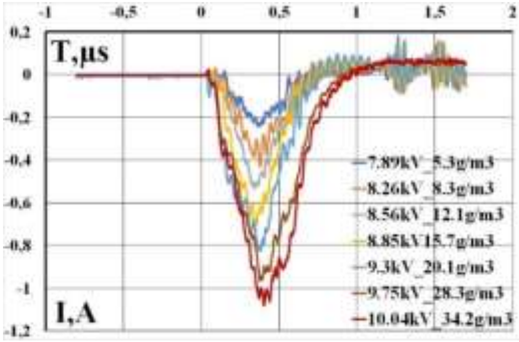

Fig. 11. Oscillograms of negative corona current pulses in a plasma-chemical reactor in oxygen at a central rod rotation speed of 15600 rpm

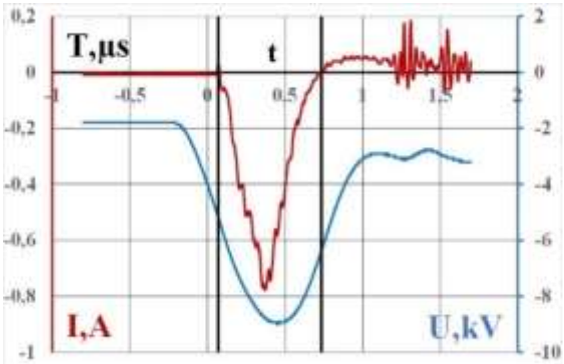

Fig. 12. Separate time interval from the beginning of the current pulse to the moment when the discharge current changes direction

In Fig. 13 shows the dependence of the negative corona pulse current on the amplitude of the high-voltage pulse. The dependence shown in Fig. 13 shows that starting from a cathode rotation speed of 4600 to 12000 rpm, a monotonic expansion of the voltage pulse amplitude range and a corresponding increase in the pulse current are observed. When the rotation speed is accelerated from 12000 to 15600 rpm, a significant increase in both the pulse current and the maximum amplitude of the voltage pulse is observed.

Fig. 14 shows the dependence of the concentration of ozone synthesized in the discharge on the power released in the discharge during a current pulse for different rotational speeds of the central rod. Fig. 15 shows the dependence of the energy efficiency of ozone synthesis, which is the amount of energy required to synthesize one gram of ozone, on the concentration of ozone, for different speeds of rotation of the central rod.

From the curves in Figs. 14 and 15, it can be concluded that the movement of the cathodes relative to the anode does not lead to a change in the conditions under which ozone synthesis occurs in the range of high-voltage pulse amplitude common to the curves.

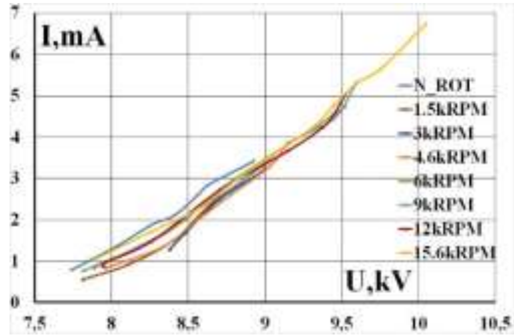

Fig. 13. Dependence of the negative corona pulse current in a plasma-chemical reactor in oxygen on the amplitude of the high-voltage pulse

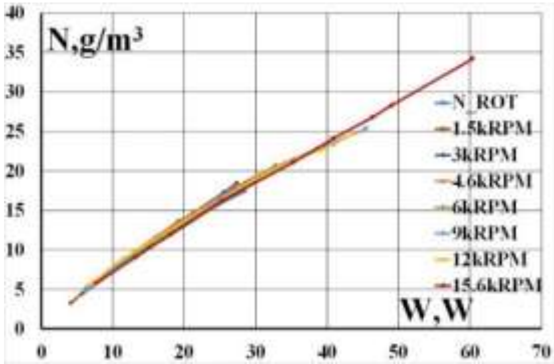

Fig. 14. Dependence of the concentration of ozone synthesized in the reactor on the power input to the discharge

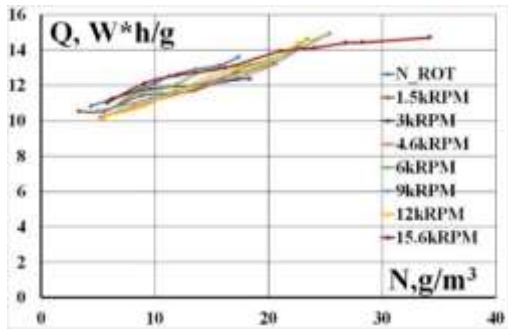

Fig. 15. Dependence of energy efficiency of ozone synthesis on ozone concentration for different rotation speeds of the central rod

3. DISCUSSION OF THE EXPERIMENTAL RESULTS

The results of the experiments shown in Figs. 14 and 15 indicate that the energy efficiency of ozone synthesis does not depend on the cathode speed. This indicates identical discharge conditions under which ozone synthesis occurs. The increase in ozone concentration with cathode acceleration is a consequence of the increase in power that can be introduced into the discharge due to the increase in the amplitude of high-voltage pulses and the pulsed discharge current.

The results of the experiments shown in Figs. 8–11 and Fig. 13 indicate that in the common, for each pair of curves, section of the range of high voltage pulse amplitudes, the electrodynamic characteristics of the negative corona are identical for all studied rotation speeds of the central rod. The identity of the electrodynamic characteristics means that the conditions under which the current pulse develops are also similar and do not depend on the speed of the cathodes relative to the anode. Increasing the speed of cathode movement increases the amplitude of high-voltage pulses at which the negative corona transitions to spark discharge. From this it can be concluded that the transition to spark occurs under the influence of specific factors that have little effect on the development of the current pulse, but provoke the transition to spark. Such factors may include the presence of a negative charge in the discharge space, its location, and the geometric shape of the clot. Negative ions serve as a positive source of background electrons for the development of the streamer, which leads to spark breakdown. From the data we have, it is possible to estimate the distance by which the negative charge is removed during the time between high-voltage pulses. The length of the discharge gap is 4.5 mm during the time between high-voltage pulses of 1.7 kV, given that the mobility of negative ions in oxygen is 2.2 $cm^2/V/s$, according to $v = \mu \cdot E$, we have a distance of 0.558 mm along the axis of the discharge gap. The cluster of negative ions drifting in an external electric field toward the cathode also expands under the influence of its own Coulomb field. At a central rod rotation speed of 4600 rpm (6.98 m/s), during the time between high voltage pulses, the cathode is displaced by a distance of 0.465 mm, which is close to the distance by which the negative charge moves away from the cathode (0.558 mm). It can be assumed that at this distance from the center of the negative ion cluster, their density begins to decrease, which increases the spark voltage. With a further increase in the rotation speed, the cathode moves even further away from the center of the negative ion cluster, so the maximum possible amplitude of high-voltage pulses increases even more. At a cathode speed of 22.77 m/s (15600 rpm), the maximum possible amplitude of high-voltage pulses is more than 1 kV compared to a stationary cathode or when the cathode is moving at speeds up to 6.98 m/s. The maximum pulse current and ozone concentration at a cathode velocity of 22.77 m/s is almost twice as high as when the cathode velocity is less than 6.98 m/s.

CONCLUSIONS

In this work, the pulsed negative corona in oxygen in an electrode system with a moving cathode was studied.

It is shown that under these discharge conditions, at a high voltage pulse frequency of 15 kHz, there is a limiting cathode velocity of 6.98 m/s, upon reaching which the maximum amplitude of the high voltage pulse increases, exceeding which the negative corona turns into a spark.

The more the cathode movement speed exceeds 6.98 m/s, the greater the value of the maximum voltage amplitude of the high-voltage pulse that can be applied to the discharge gap without going into the spark stage. At a cathode velocity of 22.77 m/s, the voltage of the negative corona to spark transition increases by more than 1 kV compared to a stationary cathode.

The maximum pulse current of the negative corona at a cathode velocity of 22.77 m/s is almost twice as high as the pulse current at a stationary cathode.

The maximum ozone concentration at a cathode velocity of 22.77 m/s is also twice as high as with a stationary cathode.

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ДОСЛІДЖЕННЯ ІМПУЛЬСНОЇ НЕГАТИВНОЇ КОРОНИ У КИСНІ В ЕЛЕКТРОДНІЙ СИСТЕМІ З РУХОМИМ КАТОДОМ

Б.Б. Кадолін, Г.В. Таран, М.О. Єгоров, В.М. Артеменко

Проведено дослідження імпульсної негативної корони у кисні при комбінованому живленні у електродній системі з рухомим катодом, її електродинамічних характеристик та кількості синтезованого озону в залежності від швидкості руху катода. Показано, що при перевищенні порогової швидкості руху катода у 6,98 м/с спостерігається збільшення максимальної можливої амплітуди високовольтного імпульсу, імпульсного струму негативної корони та кількості синтезованого озону. При швидкості руху катода 22,77 м/с амплітуда високовольтного імпульсу збільшується відносно нерухомого катода на 1,15 кВ, імпульсний струм та кількість синтезованого озону збільшились у двічі.