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Development and Research of the Ozonator at the Crow-Barrier Discharge

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Abstract

Based on the electrical properties of the corona discharge on microelectrodes, a new type of corona-barrier discharge ozonizer has been developed and tested, which differs from the known corona discharge ozonizers (CDO) in its simplicity of design, reliable operation and low specific energy consumption for ozone generation. In this case, the corona wire is spirally wound on a dielectric tube (barrier), inside of which a second external electrode in the form of a cylinder is located coaxially and, when a high-frequency high-voltage is applied to this electrode, the electrical safety of the ozonizer as a whole is ensured. In addition, the electric field was calculated in the area of the location of the corona wire spiral, which made it possible to find the field strengths at the "special" points of ozone formation near the wire.

Keywords: corona-barrier discharge, ozonizer, microwire, high-voltage pulse generator, current-voltage characteristics, ozone productivity.

I. INTRODUCTION

The most widely known are barrier discharge electric ozonizers, which are designed to generate a large amount of ozone (kg/h and more) and are used in various industries. Usually, high-voltage alternating voltages with a frequency of 50 Hz and higher are used to power such ozonizers [1-3]. For household, sanitary and economic purposes, small-sized corona discharge ozonizers of the CDO type have been developed, which belong to the category of ozonizers of average ozone productivity (10 – 100 g/h) with an ozone energy output 30 – 40 g/kW*h [4-6]. The combination of the two principles for the production of ozone at the barrier and corona discharges made it possible to increase the specific energy yield of ozone and, in general, to increase the productivity of the ozonizer. At the same time, in the barrier discharge, the current decrease in the efficiency of ozone output is excluded due to its passage when purging through the interelectrode space, where the ionization processes of ozone formation intensively occur. The main disadvantage of corona discharge ozonizers is the fragility and evanescence of the corona microwires (50 – 100 micron), which ultimately leads to inconvenience during operation due to their frequent exchangeability [7-8].

II. DEVELOPMENT OF CORONA_BARRIER OZONIZERS

Corona-barrier discharge ozonizers are distinguished by their simplicity of design, low supply voltages and high energy outputs of ozone (50 – 60g/kW h) in comparison with previous ozone generators by type CDO [9-11[. Corona-barrier ozonizers have a rigid structure, also are durable and reliable in operation. The right choice of the corona-barrier principle for producing ozone is confirmed by the highest energy output of the ozonizer (170 g/ kW h) [12], where "high" technology was used in its manufacture and unique ceramics as a dielectric barrier. In this regard, it should be noted that in the case of a barrier discharge, the material of the dielectric wall plays a decisive role in the electrosynthesis of ozone.

The ozonizer is made in the form of a dielectric tube (barrier), on which a corona wire is spirally wound with a spiral pitch more significant than the tube wall thickness, and an external electrode in the form of a cylinder is located coaxially inside the tube. The ozonizer is equipped with a half-wave rectifier and a chamber for neutralizing ozone ions, made of two metal grids connected to a corona electrode (figure 1).

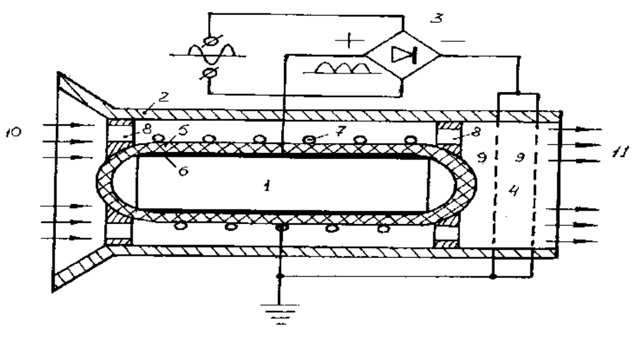

Fig. 1. Coronary-barrier ozonizer

The ozonizer consists of an ozonizing element 1, a body made of dielectric material 2, a half-wave rectifier 3 and a chamber for neutralizing ozone ions 4. The ozonizing element 1 contains a dielectric tube 5, that encloses the outer electrode 6 and the corona wire 7, which is wound in a spiral around the dielectric tube 5. The ozonizing element 1 is fixed inside the body of the ozonizer 2 by holders of dielectric material. 8. A room for neutralizing ozone ions is formed by two mesh

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electrodes 9, located under the potential of the corona electrode 7 [11].

The ozonizer operates on a corona-barrier discharge as follows: when a positive half-wave of the high alternating voltage is applied to the external electrode, a negative corona-barrier discharge occurs between the last and corona electrodes which allow the generation of ozone in atmospheric air 10, blown through the discharge gap. At the same time, at the exit from the chamber for neutralizing ozone ions, ozonized air 11 with neutral ozone molecules is obtained. For proper operation of the ozonizer [17-19], it is necessary that the pitch of the corona wire spiral is greater than the distance from it to the external electrode, i.e. thickness of the dielectric barrier. In addition, it is necessary to provide breakdown voltage (not less than 10 kV/mm) in comparison with the operating voltage between the outer electrode and the corona wire.

The ozonizer is made in the form of a dielectric cylinder of glass 100 mm long, on which a corona wire with a diameter of 0.1 mm is wound with a winding pitch of 3 mm. The wall thickness of the dielectric cylinder is 2 mm, and the diameter is 18mm. The external electrode is a metal cylinder (length 90mm, thickness 2mm), located coaxially and inside the glass tube. The cylindrical shape ozonizer body is made of vinyl plastic with a length of 140 mm and a diameter of 32 mm, and the gap between the frame and the dielectric cylinder blown by air is 5–7 mm. A power source with an adjustable output voltage from 1 to 4 kV with a frequency of 400 Hz was used, its power is 6W. The maximum specific yield of the product at an operating voltage of 3.2 kV and a current of 0.41 mA was 61 g of ozone per 1, and the productivity of the ozonizer was 0.08 g of ozone per hour.

III. ELECTRICAL CALCULATION OF THE OZONIZING ELEMENT ON THE CORONA-BARRIER DISCHARGE

Despite a large number of works devoted to calculating electric fields, specialists face significant difficulties due to the non-standard nature of the task, therefore, the complexity of the shape of the fields. In addition, most of the calculated fields are of plane-parallel or axisymmetric type, while the electrostatic fields of actual structures are spatial. If in the case when the Laplace equation is easily transformed to the ordinary differential one, which uniquely determines the field strengths in the interelectrode gap, then for more complex structures, they usually look for a function that would make it possible to construct a field distribution picture from the points.

In our case, the object of electric field calculation is an ozonizing element on a corona-barrier discharge, where a spiral of thin wire (microwire, 100 microns), wound on a glass cylinder inside which a second electrode is located is used as the corona electrode. Figure 2 shows the calculation scheme of the ozonizing element, which shows the coordinate system and dimensional designations for the calculation.

The view of the small diameter of the spiral and the equal inter-turn distance (a = 0,4mm, b = 0,1mm, d = 0,5mm) with it compared to the size of the glass cylinder and to simplify the task, the spiral winding of the corona electrode can be represented as a flat system of parallel wires of infinite length with equal gaps between them. In this case, it will be about determining the electric field near the grid, as if composed of charged wires. Far from the grid, we observe a uniform electric field with a strength of $2\pi\sigma$ (σ – surface charge density), as if the charge was uniformly distributed on the plane. For our case, σ is determined by the ratio τ/d, where τ is the charge per unit length of the charged wire. In this case, the field strength is directed along the z-axis from above the spiral ($z > 0$) and against the z-axis from below ($z < 0$), and the potential of this field will have the form $2\pi\sigma$.

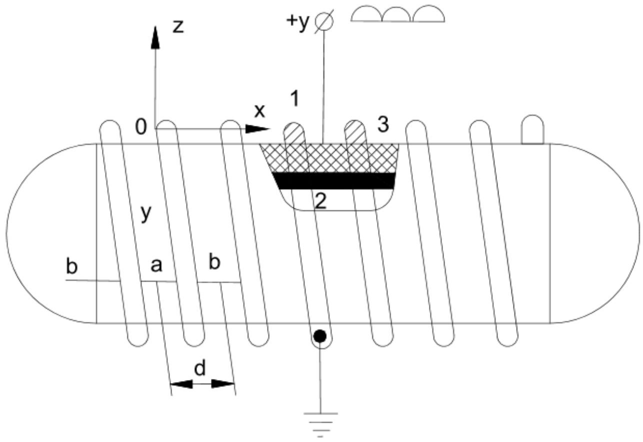

Fig. 2. The design scheme of the ozonizing element: 1 - spiral, 2 - second electrode, 3 - glass cylinder

As approaching the grid (spiral), deviations from the previous uniformity will begin. The closer to the grid, the stronger the field fluctuations and the more noticeable changes in potential. Now the potential is no longer determined by the formula $2\pi\sigma$, but depends not only on z but also on x, since moving parallel to the spiral, we observe how the field changes periodically. As it's known, any periodic value can be represented as the sum of sine waves (Fourier theorem). Therefore, the task is to find a suitable vibrational function that would satisfy our field equations.

If the wires lie in the XY plane parallel to the y-axis and assume that they are very long, then no changes in the field along y are observed. In addition, the field near the wire, as the field of a charged single-cylinder, will be determined by the ratio $E = 2\tau/r$, which allows calculating the field potential

$$U = U_0 - 2\tau \ln \frac{r}{r_0},$$

where r0 is the radius of the wire; U0 – potential on the surface of the wire; r is the radius of the equipotential line where the potential is sought.

The translation of r0, r into the Cartesian coordinate system of the calculation scheme gives r0 = b/2 and $r = \sqrt{z^2 + x^2}$ for the cases when $x \geq 0$.

Thus, in order to obtain the true potential in the region where there are no charges, it must obey the Laplace

$$\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial z^2}=0, \quad (1)$$

equation, whose solution is sought in the form

$$U(x,z)=U_0-2\tau\ln\frac{2\sqrt{z^2+x^2}}{b}+\psi(x,z), \quad (2)$$

where ψ(x, z) is some function of two variables that disappears when it is $|z| \to \infty|$. The function ψ(x, z) must be periodic in x with a period d = a + b, equal to the distance between the centres of two adjacent gaps (figure 3). Like the U, the function ψ(x, z satisfies the Laplace equation

$$\frac{\partial^2 \psi(x,z)}{\partial x^2}+\frac{\partial^2 \psi(x,z)}{\partial z^2}=0, \quad (3)$$

and it can be represented as a Fourier series

$$\psi(x,z)=\sum_{n=0}^{\infty}\Phi_n(z)\cos\frac{2\pi nx}{d}, \quad (4)$$

where Φn(z) is the Fourier coefficients representing some functions of z; n is the number of oscillations.

After determining the function ψ(x, z) using the Fourier series and solving the equation (2), in the end, we find the calculated values for the field strengths EX and EZ.

When the formulas for determining Ex and Ez and other necessary data for calculation are known, we will again return to the accepted designations and sizes of the spiral electrode shown in Figure 2. Figure 3 shows a more visual picture of the section of several turns of the spiral, where the coordinate system is indicated, designations of location turns of the spiral and "special" points where it is necessary to determine the field strength.

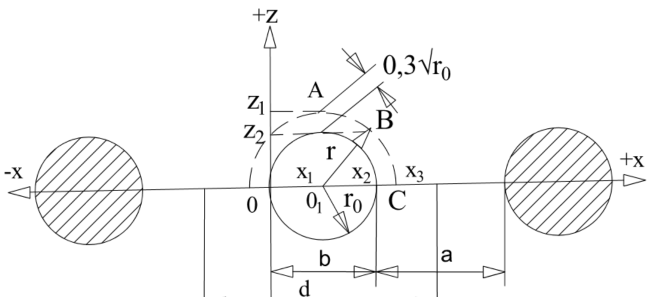

Fig. 3. Field calculation scheme

Accepted calculation data: a = 0,04cm, b = 0,01cm, d = 0,05cm, U0 = 5÷10 kV, $r_0=\frac{b}{2}=0{,}005$ cm, $r=r_0+0{,}3\sqrt{r_0}$ = 0,026cm.

Define the constant values of some expressions that are necessary for the calculation

τ = 27,3 k / m for U0 = 1kV; 54,6 – U0 = 2kV; 109,2 – U0 = 4kV;

B = – 17,8; $\sin\frac{\pi a}{d}=0{,}587;\quad \sin\frac{2\pi a}{d}=0{,}953.$

$ctg\frac{\pi a}{d}=\ 1{,}375;\quad ctg\frac{2\pi a}{d}=\ 0{,}325.$

calculate the values of Ex and Ez for some boundary points of the circuit in Figure 4. When z = 0, $\mathbf{x=\frac{a}{2}}$

Ex = 180 kV / cm; Ez = – 123,2 kV / cm.

When z = d; x = 0

Ex = 0; Ez = – 1,28kV/ cm

The second case refers to a point lying above the surface of the wire along the line z when x = 0. It follows that with distance from the wire, the values of the variable field (Ex, Ez) components will decrease sharply. Of interest is the value of the field near the wire at a distance of $0{,}3\sqrt{r_0}$, since this distance ultimately determines the thickness of the corona layer [6].

For field strength in the case x = 0,005cm, z = 0,026cm и U0 = – 1kV, we obtain the following

Ex = – 88,57kV/cm; Ez = – 137,7kV/cm;
E = 163,75kV/cm.

Thus, the calculated expressions Ex, and Ez are obtained for determining the fields of parallel wires equally spaced from each other, which have a geometric similarity with the spiral of the corona electrode in the ozonizing element [1]. This situation became possible only due to the fact that microwire (100 micron) was used as the corona electrode. The obtained method for calculating the field strengths near the corona electrode makes it possible to determine the geometric parameters of the ozonizing element that provide the necessary ozone characteristics of the ozonizer.

IV. AN EXPERIMENTAL STUDY OF A CORONA-BARRIER OZONIZER

To study the electrical and ozone characteristics of the ozonizer, an experimental setup was developed and assembled. Figure 4 shows a block diagram of an experimental installation for wastewater treatment. The device contains a compressor, an airflow meter (rotameter), an ozonizer, the supply voltage to which is supplied through an autotransformer that is connected to an alternating current network ~220 V, a power supply (PS) unit, an ozonometer, and a test link. A gas analyzer is used to measure ozone concentration «OZON-5-200».. During operation, atmospheric air is pumped into the ozonizer using a compressor, at the outlet of which an ozone-air mixture is formed, which enters the tank with wastewater.

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For convenience, simplified design of the ozonizing element has been developed, where plastic fluor with a high dielectric constant is used as a barrier. High voltage pulses with a duration of 75 mks and a frequency of up to 4 kHz are used to power the ozonizing element in the corona-barrier discharge.

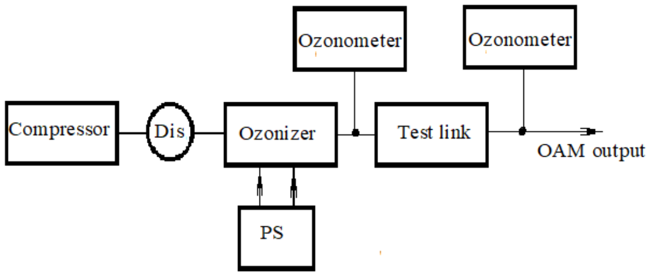

Fig. 4. The structure diagram of the experimental setup

Figure 5 shows the design of an individual ozonizing element and its section on an enlarged scale of the electrodes. A metal foil (aluminum, bronze, copper) is applied to the glass flask of cylindrical shape as a second electrode, and then a 1-2 mm thick polytethraflourethylene film is applied to it as an electric barrier. A corona electrode in the form of a tungsten microwire and with a diameter of 50 mks is wound in a spiral with a pitch of 2 mm on top of the PTFE film. When a high-frequency voltage of sufficient magnitude is applied to the second electrode, a corona discharge occurs in the microwire, which ensures the appearance of ozone near the corona electrode.

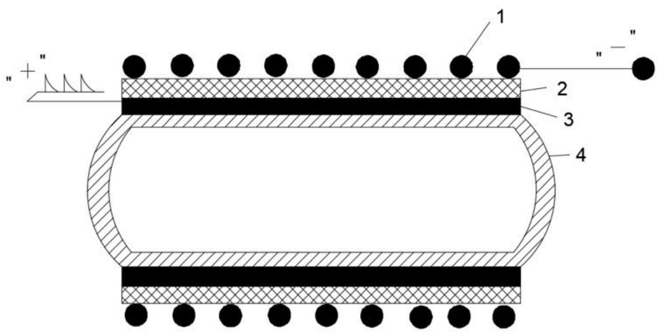

Fig. 5. Design of an ozonizing element on a corona-barrier discharge: 1 - corona electrode-microwire; 2 - a barrier of a dielectric material-fluoroplastic; 3 - the second electrode is a metal foil; 4 - a cylindrical flask from a dielectric - glass, ceramics.

It should be noted that the ozonation block consists of four such ozonizing elements.

The high-voltage pulse generating unit, which is essentially a thyristor high-voltage inverter operates (THVI) at a selected frequency from the range (0.5-4 kHz),and is connected to a 220V, 50Hz network through a laboratory autotransformer (LATF), which allows increasing the supply voltage of the thyristor high-voltage inverter smoothly THVI. (fig.6).

Adjustable AC voltage is supplied to the main rectifier, a constant voltage from which feeds the thyristor switch. The power thyristor control electrode is triggered by a pulse from a low-power master oscillator through a transistor-type logic amplifier. The low-power part of the thyristor high-voltage inverter receives power from a separate low-voltage source, which is a rectifier and a parametric stabilizer at +5 V to power TTL microcircuits (transistor-transistor logic).

The electrical circuit diagram of the thyristor high-voltage inverter is shown in Figure 7.

The basis of the unit is a power thyristor type KU202H (which can withstand forward and reverse voltage up to 400 V). A pulse arrester of storage capacity C2 is made on it through the primary winding of a step-up transformer TP2. The thyristor is a power electronic not fully controlled key. Therefore, sometimes in the technical literature, it is called a single-operation thyristor, which can be translated by a control signal only into a conducting state, i.e. turn on. To turn it off (when working on direct current), special measures must be taken to ensure that the direct current drops to zero.

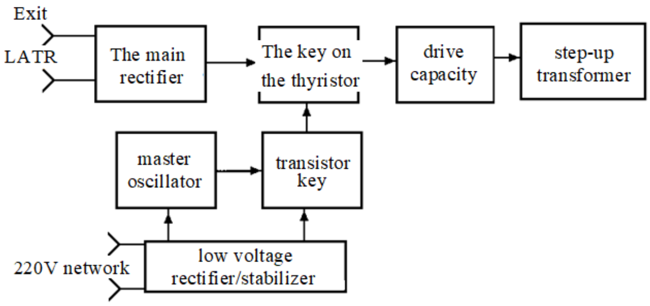

Fig. 6. The structural diagram of THVI

The thyristor switch can conduct current only in one direction, and when closed, it can withstand both forward and reverse voltage. The duration of the transition process depends on the nature of the load, amplitude and slew rate in the control circuit. Moreover, it should be positive (with respect to the cathode). The duration of the transition process depends on the nature of the load (inductive, active), amplitude and slew rate in the control circuit.

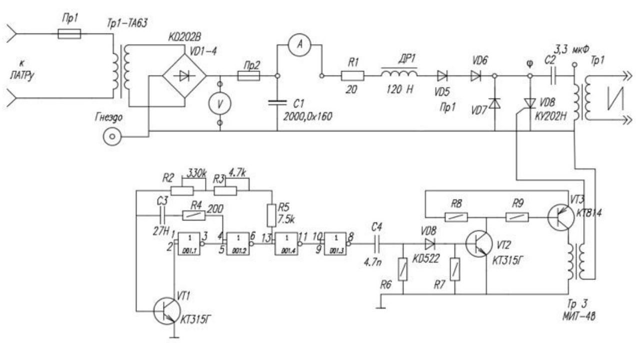

Fig. 7. Thyristor high-voltage inverter with a master oscillator

The master pulse generator is made according to the scheme of a multivibrator-oscillator on a microchip (IC) TTL logic chip of the K155la12 type, on two elements of which (DD1.1, DD1.2), a capacitor C3 and resistors R2, R3, R5 an RC generator is assembled. The frequency regulation of rectangular pulses is carried out by variable resistors R2 (roughly) and R3 (exactly). R5 limits the current of the IC and sets the maximum frequency of the generator. The elements of the IC (DD1.3, DD1.4) isolate the output of the generator and the load, which is the transistor switch on the transistor VT2 (type KT315g) with an additional amplifier-driver on the transistor VT3 (type KT814B), in the collector circuit of which is included a pulse transformer Tr3 (small-sized transformer MIT-4V). The use of a transformer allows galvanic isolation of the high-voltage and low-voltage "piles of earth". The main rectifier for supplying direct voltage to the thyristor consists of a network transformer type TA-63, a diode bridge on VD1-4, a smoothing capacitive filter on an electrolytic capacitor C1, the voltage from which is supplied through a limiting resistor R1, inductor DR1 and powerful diodes VD5, VD6 to thyristor anode. The thyristor is unlocked by pulses coming from the master oscillator, while the capacitor C2 is discharged through it and also through the primary winding of the step-up transformer TP2, while high-voltage pulses are induced on the secondary winding. Diodes VD5 and VD6 (type KD202R, reverse voltage up to 600 V) prevent the discharge pulses of reverse polarity from entering the main rectifier circuit, and the VD7 (type KD202R) diode prevents the breakdown of the thyristor VD8 from reverse voltage 8 (emf self-induction TP2).

V. RESULTS

The electrical characteristics of the corona-barrier ozonizer are closest to the characteristics of the corona discharge on microwires, as such is the current-voltage characteristics and initial voltages field of the appearance of the corona discharge. Due to the fact that high-voltage and high-frequency voltage pulses in the form of a triangle with a steep front are used to supply the ozonizer, it constructs the current-voltage characteristics more correctly from the values of the amplitudes of the currents and voltage pulses. Figure 8 shows the current-voltage characteristic of the corona-barrier discharge ozonizer for frequencies of 4 kHz.

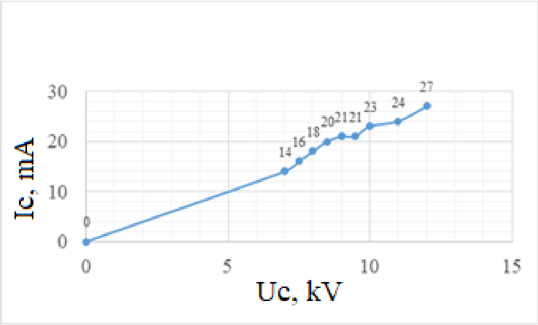

Fig. 8. Current-voltage characteristic of the ozonizer.

The current-voltage characteristic is important for choosing the electrical parameters of the ozonizing element of the ozonizer. To measure the values of currents and voltages of pulsed signals, the oscillographic method using dividers and loads from reference resistances was used. As follows from the current-voltage characteristics, the microwire begins to corona from voltage Uкор = 7 kV. The presence of the ozonizer current to this voltage is explained by the presence of interelectrode geometric capacitance.

Ozone characteristics include ozone performance for ozone (g/h) and specific energy yields of ozone (g/kW * h). In addition, one of the characteristic parameters of the ozonizer is the volume concentration of ozone in the ozone-air mixture at the outlet (Ko3, mg/l).

Table 1. The output of the ozonizer

Uc, kV	7,0	7,5	8	8,5	9	9,5	10	11	12
Ic, mA	14	16	18	20	21	21	23	24	27
Pcon, W	98	120	144	170	189	199,5	230	264	324
O3, g/h	0,1	0,2	0,35	0,54	0,72	0,91	1,24	1,68	2
O3, g / kWh	65	64,2	63	62,4	59	54,54	48,54	47,03	45,01
KO3, mg/l	0,1	0,75	1,32	1,98	2,64	3,3	4,62	6,16	6,6

In this table, using a gas analyzer «OZON-5-200», we determined the performance of the ozonizer (g/h) at various currents, and then the specific energy outputs of ozone were calculated from the electrical characteristics (g/kW*h). According to the readings of the rotameter, the volume concentrations of ozone Ko3 at the output of the ozonizer were determined.

The developed ozonizer was tested during the ozone treatment of oily wastewater. Ozonator tests showed that ozone has an excellent effect of removing oil products from water under conditions of 23°C pH 7,2, 4,0 mg/l of ozone and a reaction time of 10 minutes (at test concentration of pollutant). The oil content is reduced from 5.0 mg/l to 0.1 mg/l, and the average removal efficiency is 82.50% after treatment with ozone.

In general, ozone can change the composition and structure of petroleum products and oxidize high molecular organic substances into low molecular weight organic compounds and even decompose some organic substances directly into CO_2 and H_2O. As a result, non-biodegradable organic substances in raw water are converted to biodegradable organic substances. In other words, pollutants can be effectively removed from the water using ozone [13-14].

Using the external area of the corona discharge, a device was developed for measuring the velocity of broaching dielectric filaments, including optical fibers during its production [15]. Using the initial portion of the current-voltage characteristic of the positive corona discharge while the corona discharge is in the “standby” mode, a device has been developed for measuring the diameter of moving dielectric filaments, including optical fiber in the process of drawing it on the exhaust tower [16].

VI. CONCLUSIONS

A new type of ozonizer was developed and tested on a corona-barrier discharge, which differs from the well-known ozonizers of the OCD type in its high specific energy output of ozone, simplicity of design, and reliability in operation.

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