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ENERGY-EFFICIENT TECHNOLOGY FOR WATER DISINFECTION IN A FLOW USING PULSED HIGH-VOLTAGE DISCHARGES

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Pulsed high-voltage discharges in gas bubbles were used during the disinfection of water in a flow. It has been shown that energy consumption can be significantly reduced compared to the experimental obtained specific energy consumption of 660 (W·h)/m³, as well as compared to ultraviolet treatment or ozonation, by shortening the rise time of current and voltage pulses to 1 ns and the total pulse duration to 10 ns.

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INTRODUCTION

Among the discharge methods of water disinfection and purification, methods based on electrical discharges in gas bubbles or in water-air mixtures are increasingly interesting [1−3]. Basically, these methods use electrode systems in which gas bubbles in the treated water form between the electrodes. Here, electrical discharges are generated in some bubbles.

There is also a known method for disinfecting and purifying water using a barrier discharge by passing water drops through a gas gap inside an electrode system with a dielectric barrier [4].

We use a flow-of-water treatment method in which a high-voltage electrode is located inside a gas bubble, which ensures a guaranteed discharge in each bubble [5].

Disinfecting water treatment using discharges in gas bubbles has the advantage over ozonation and ultraviolet treatment because one uses the entire spectrum of high-intensity factors from discharges in bubbles: electrons with an energy of about 10 eV or more, microparticles, including OH radicals, broadband radiation from discharges, including ultraviolet and shorter wavelength radiation. All these factors end up in the water. In addition, more than 90% of the total voltage is applied to the water layer because of discharges in gas bubbles inside the water. As a result, a strong electric field with a strength of approximately 50 kV/cm is created in the water layer, which is also an active factor. Water, the subject (object) of treatment, is also a barrier that prevents short circuits during discharges in gas bubbles.

During discharges of nanosecond duration in bubbles, which are the most energy-saving, the formation of volumetric streamers (primary clouds) [6] is possible in each of them, occupying the entire volume of the bubble and providing a voltage drop and an increase in current in the bubble at the initial stage (switching stage) of nanosecond discharges. This circumstance further reduces the specific energy consumption when disinfecting water with nanosecond discharges in gas bubbles (inside it).

This work aims to investigate and optimize the process of water disinfection in flow using pulsed high-voltage discharges in gas bubbles, emphasizing minimal energy consumption while maximizing the efficiency of microorganism disinfection.

EXPERIMENTAL RESULTS

The experimental results of our studies on water disinfecting treatment in a flow with pulsed discharges in gas bubbles are presented (in detail) in [5]. The experimental plant contains three reactors − discharge units, electrically connected in parallel, through which the water that subjects disinfection flows sequentially. The high-voltage switch consists of three multi-gap multi-channel dischargers which operate in parallel and provide a pulse repetition rate of up to f_{rpt}≈2500 p/s. We use a low-inductance current shunt and a capacitive voltage divider for current and voltage measurements (consequently). R_{sh} is the resistance of the measuring shunt; R_{m1}=300 Ω, R_{m2}=60 Ω − matching shunt resistances, R_{sh}=2.5 Ω; C_1, C_2 − capacitances of the high-voltage and low-voltage arms of the capacitive voltage divider *CDV* ($C_1 \approx 2.7 \cdot 10^{-12}$ F, $C_2 = 20.4 \cdot 10^{-9}$ F, division ratio $k_d \approx 7650$) with matching resistance R_m=50 Ω; $C_d << C_{ec} << C_0$. In the electrical circuit of each of the three discharge nodes (reactors) C_d, R_d − capacitance and nonlinear active resistance of the discharge gap in the gas bubble, and *C*, *R* − capacitance and nonlinear active resistance of the water layer between the discharge gap (DG) and the grounded electrode.

Fig. 1 shows structural diagram of the experimental stand implementing this method. Experimental plant consists of a low-impedance generator 1 of high voltage pulses, compressor 2, pump 3, pipeline 4 with a diameter of *D*=40 mm with running water, made of insulating material. The plant includes also three branch pipes 5 with a diameter of D_{bp}=40 mm, through which insulation hollow cases 6 without a bottom are inserted and fixed there. Cases 6 are made combined with high-voltage conductors − pointed electrodes 7 in isolation and with tubular gas pipelines 8. The plant contains also a grounded electrode 9 in each of the three discharge units. This electrode is made in the form of a metal cylindrical ring with a hole in its side surface for the location of the case 6 in the pipeline 4.

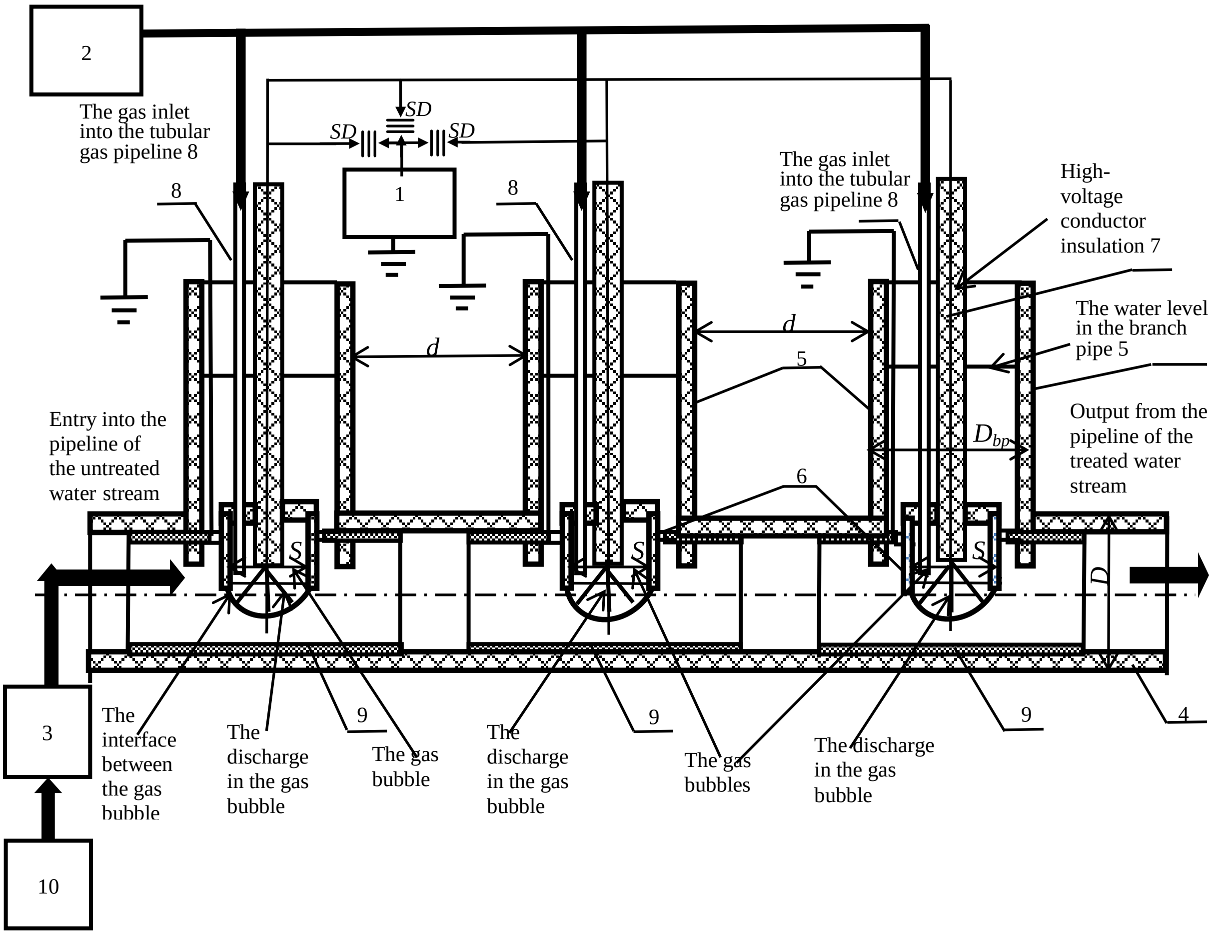

Fig. 1. Structural diagram of the experimental stand [5]

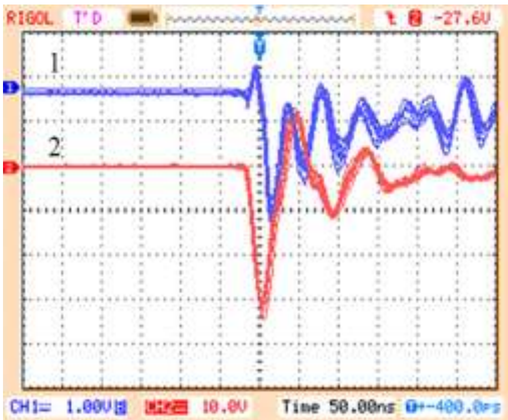

Fig. 2. Experimental pulses in the reactor:
1 − voltage pulse; 2 − current pulse

Each discharge unit consists of an electrode 7 in solid insulation, the tip of which is not insulated, a case 6 with a characteristic internal linear size S=2.8 cm, a gas-pipe 8, an electrode 9 and a water layer inside the pipe 4 under and around the branch pipe 5. The branch pipes 5 may have caps (Fig. 2 not shows caps) with the possibility of gas outlet after discharges in gas bubbles. Wherein, the outflow of water through the caps on the branch pipes 5 is impossible. A pump 3 pumps water into a pipe 4 from a water source 10. The distance between adjacent branch pipes is d≈300 mm. The flow rate of water and gas from the compressor is adjustable. The composition of the gas may be different. The flow of water can be carried out by gravity from a source of water 10.

Fig. 2 shows the waveforms of voltage pulses (curves 1) and current (curves 2) for a variant with three reactors connected in parallel and with three multigap gas discharges included in parallel. Oscillograms in Fig. 2 with several voltage and current pulses are superimposed on each other. This overlay shows good pulse repeatability.

After treating the water in the stream with discharges in gas bubbles, the pulses shown in Fig. 2, within 35 s at a pulse repetition rate of f_{rpt}≈2400 p/s, complete inactivation of E. coli bacteria was achieved. The results of the analyses are shown in the Table.

The seeding by indicative microorganisms − E. coli bacteria and analyzes of treated and control water samples were carried out in the specialized enterprise "Sanepidservice" (Kharkiv, UA). The initial seeding (bacterial concentration, number of bacteria per unit volume) of both the experimental and control samples was 10^6 CFU/cm^3 (CFU − colony forming units). This is a very high concentration, at least 100 times higher than the maximum concentration of E. coli bacteria in real dirty wastewater.

An important characteristic is the specific energy consumption of W_{sec} for disinfection [7]. To reduce the obtained value W_{sec}≈660 (W·h)/m^3 in this plant, at an initial concentration of E. coli of 10^6 CFU/cm^3, there is a significant reserve. If the initial concentration decreases by a factor of 100, a corresponding additional decrease in W_{sec} should be expected. The total concentration of E. coli in the treated (experimental) sample turned out to be zero, while in the control sample the concentration (the seeding) remained equal to 10^6 CFU/cm^3.

The obtained research results

Name of indicator, units of measure	Regulatory documentation for test methods	Research result
Determination of total coliforms in drinking water or coli-index in pool water and wastewater		
Experimental sample E. coli 10^6 (CFU/cm^3) CFU − colonies forming units (water treatment by electric discharges in gas bubbles)	Methodical instructions # 10.2.1-113-2005 approved by the order of the Ministry of Health of Ukraine from 03.02.2005, No. 60	0
Control sample E. coli 10^6 (CFU/cm^3)		10^6

Fig. 3 show photos of typical discharges in gas bubbles inside a water volume during treatment. For comparison, during the treatment of an aqueous suspension using the ultraviolet method [8] with an initial concentration of E. coli at 10^6 CFU/mL, the following specific energy consumptions were calculated: for a UV-LED with a wavelength of 275 nm, the specific energy consumptions for 1 log and 2 log inactivation were 0.1367 and 0.2219 (kW·h)/m³, respectively. For longer wavelengths, such as 310 nm, the energy consumption was significantly higher, reaching 1.7576 (kW·h)/m³ for 1 log inactivation due to lower bactericidal effectiveness. After treatment, slight S. Enterica, S. Flexneri, and V. Cholerae at concentrations of 10^6 CFU/ml in 1 li of model wastewater, an ozone concentration of 20.83 mg-min/l and a treatment time of 45 min were required to achieve an inactivation level of 99.9999% [9]. Bacterial reactivation was observed. In the disinfection of E. coli, reactivation 24 h after ozonation was minimal, ranging from 0…5%. Therefore, large specific energy consumptions are needed for the disinfection of such significant bacterial concentrations during ozonation and ultraviolet treatment.

THE WATER DISINFECTION PROCESS, WHICH USES HIGH-VOLTAGE NANOSECOND DISCHARGES WITH A FRONT OF ABOUT 1 ns IN GAS BUBBLES

It is necessary to reduce the duration of voltage and current pulses in the treated water as much as possible without reducing the amplitude of the pulses and without significantly increasing the cost of the processing plant to reduce specific energy consumption when treating water. Reducing the pulse duration to 10 ns does not currently cause significant technical issues but allows for a reduction in undesirable energy losses due to the heating of the treated water. However, for the amplitude of the pulses in the reactor(s) with treated water not to decrease, the duration of the pulse front must be 5–10 times less than the pulse duration, i.e. with a pulse duration of 10 ns, the duration of its front should be 1…2 ns. High-speed dischargers (gas spark gaps) and SOS (SOS − semiconducting opening switches) diodes can provide such a rise time on a low-inductive load with a resistance of ≈50 Ω or more.

We assumed in [10] (based on experimental results), that it is possible to achieve a switching time of a high-voltage gas discharger of approximately 1 ns if a primary ionization zone formed in the discharge gap, covers the entire discharge gap.

Fig. 3. Photos of high-voltage pulsed discharges in gas bubbles during water treatment

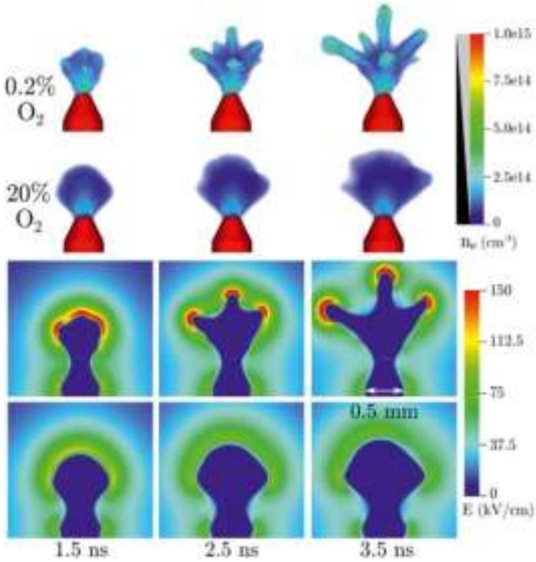

Fig. 4. Electron density (top) and electric field strength in the cross section (bottom)

The results of computer simulation, presented in [6], confirm the assumption made in [10].

Fig. 4 shows volumetric plasma formations (primary clouds) at the tip of a needle electrode (see [6]) at a pressure of 1 atm. Shown: electron density (top) and electric field strength in the cross section (bottom).

The following relation is valid to determine the specific energy (1) (in a circuit with a resistive load) spent on processing water in a stream flowing at a volumetric velocity V_v,:

$$w_s = \left[\int_0^{t_p} u(t)\, i(t) dt\right] / (V_v T), \qquad (1)$$

where w_s is the specific energy spent on processing V_v; t_p is the pulse duration; $u(t)$ is the voltage in the reactor with a discharge in a gas bubble as a function of time; $i(t)$ is the current in the reactor with a discharge in a gas bubble as a function of time; T – pulse repetition period.

We get (for rectangular voltage and current pulses with an infinitely steep rise and fall at t_p=10^{-8} s, $u(t)$=*Const*=$3\cdot10^4$ V, $i(t)$=*Const*=100 A, V_v=0.15 m^3/h, T=$4\cdot10^{-4}$ s:

$w_s = t_p \times u \times i/(V_v \times T) = 10^8 \times 3\times10^4 \times 100/(0.15 \times 4\times10^4)$ = 500 (W·h)/m^3.

If the voltage and current pulses have a falling top rather than a rectangular shape (other things being equal), then the specific energy consumption ws will be significantly less than 500 (W·h)/m^3. With an aperiodic discharge of a high-voltage capacitive energy storage device with a capacitance of C=100 pF onto an active (purely resistive) load with a resistance of R=100 Ω, the decay of the peak will be exponential with a decay time constant τ e≈2.72 times τ=C×R=10^{-10} ×100=10^{-8} s.

The authors of [11] experimentally showed that a spark discharge leads to a greater degree of inactivation of E. coli bacteria in water than a streamer discharge. In this case, the current amplitude in the spark discharge was approximately 7 times greater than in the streamer discharge. This work does not show the achieved results on specific energy consumption for disinfection using various discharge options.

The specific energy consumption can be reduced, compared to that achieved in the experiments, we have already conducted. Here, the question of the most energy-efficient form of discharge remains open. We can say that the discharge begins with a primary volumetric streamer cloud, which can occupy the entire gas bubble. This cloud can transform into a pulse corona, and then into a spark discharge (or immediately into a spark discharge). The criterion for energy efficiency is the maximum microorganism's inactivation degree at the minimum permissible specific energy consumption. It is necessary to do more research to determine maximum energy efficiency.

CONCLUSIONS

Experimental results have shown that during the disinfection of water at a flow rate of 150 l/h, contaminated with E. coli at an initial concentration of 10^6 CFU/cm³, complete and irreversible inactivation of bacteria was achieved at a specific energy consumption of 660 (W·h)/m³. Further reduction in energy consumption is possible by shortening the pulse duration and rise time to a few nanoseconds without changing the amplitudes of voltage, current, and frequency. If the voltage and current pulse shapes have a declining peak instead of a rectangular one (with a front duration of 1…2 ns and a pulse duration of 10 ns), it is possible to reduce the specific energy consumption to values less than 500 W×h/m³. The primary ionized cloud (the first volumetric streamer) can occupy the entire volume of a gas bubble with a characteristic linear size of approximately ~ 1 cm if the pulse has a nanosecond front.

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ЕНЕРГОЕФЕКТИВНА ТЕХНОЛОГІЯ ЗНЕЗАРАЖЕННЯ ВОДИ У ПОТОЦІ З ВИКОРИСТАННЯМ ІМПУЛЬСНИХ ВИСОКОВОЛЬТНИХ РОЗРЯДІВ

М.І. Бойко, А.В. Макогон

Під час знезараження води у потоці використовувалися імпульсні високовольтні розряди у газових бульках. Показано, що енергоспоживання можна значно знизити у порівнянні з експериментальними питомими енерговитратами 660 (Вт·год)/м³, з ультрафіолетовою обробкою або озонуванням, скоротивши тривалість фронту імпульсів для струму та напруги до 1 нс, а загальну тривалість імпульсів – до 10 нс.