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M.I. Boiko, A.V. Makogon

Disinfectant treatment of liquids with high specific electrical conductivity by high-voltage nanosecond pulses with a subnanosecond front

Purpose. *The purpose of the work is to determine, using computer modelling, energy-efficient modes of disinfecting treatment of water-containing liquids with high specific electrical conductivity using high voltage nanosecond pulses with a subnanosecond front including pulsed discharges in gas bubbles.* ***Methods.*** *We considered methods of obtaining high-voltage nanosecond pulses with sub-nanosecond fronts. To achieve this goal, we used computer simulation using Micro-Cap 12. We also used analytical and empirical formulas for calculating the electric field strength, inductive and resistive phases of energy switching from a capacitive source to resistive-inductive loads. We have applied the method of comparing calculated and experimental results.* ***Results.*** *Energy-efficient modes of disinfecting treatment of water-containing liquids with high specific electrical conductivity using nanosecond discharges with a subnanosecond front in gas bubbles are such modes when the active resistance of the treated liquid is 10–40 Ω. In this case, the lumped inductance of the discharge circuit during liquid treatment does not exceed 2 nH, the capacitance of the layer of the treated liquid is 3.6–14 pF with an amplitude of pulses from a high-voltage low-resistance source of at least 30 kV and a pulse frequency of 1500–2000 pulses per second. With an increase in the active resistance of the liquid within the specified limits, the amplitude of the voltage on the layer of the treated liquid increases under other unchanged conditions, including with an unchanged amplitude of the voltage from the source. The voltage amplitude on the layer of the treated liquid with such an increase can exceed the voltage amplitude from the source by 1.6 times, and exceed the voltage on the reactor as a whole (the series connection of the bulk streamer and the water layer). This happens due to the presence of a lumped inductance in the discharge circuit, in which energy is stored during discharge.* ***Scientific novelty.*** *We have shown the possibility of using nanosecond discharges with sub-nanosecond fronts in gas bubbles for energy-efficient disinfection of liquids, including those with high specific electrical conductivity. In this case, a plasma electrode – a volumetric streamer – acts as a high-voltage electrode in the disinfection of liquids.* ***Practical value.*** *The obtained of the computer modelling results confirm the possibility of industrial application of nanosecond discharges with a sub-nanosecond front for disinfection and purification of water-containing liquids with high specific electrical conductivity.* References 23, figures 13.

Key words: **water disinfection with high-voltage pulses, discharge unit, high-voltage streamer plasma electrode, nanosecond discharge in gas bubbles in water, long electric line, sub-nanosecond rise time of high voltage.**

Мета. *Метою роботи є визначення за допомогою комп'ютерного моделювання енергоефективних режимів дезінфікуючої обробки водовмісних рідин з високою питомою електропровідністю з використанням високовольтних наносекундних імпульсів із субнаносекундним фронтом, включаючи імпульсні розряди в газових бульбашках.* ***Методи.*** *Розглянуто методи отримання високовольтних наносекундних імпульсів із субнаносекундними фронтами. Для досягнення цієї мети було використано комп'ютерне моделювання за допомогою Micro-Cap 12. Також було використано аналітичні та емпіричні формули для розрахунку напруженості електричного поля, індуктивної та резистивної фаз перемикання енергії від ємнісного джерела до резистивно-індуктивних навантажень. Застосовано метод порівняння розрахункових та експериментальних результатів.* ***Результати.*** *Енергоефективними режимами дезінфікуючої обробки водовмісних рідин з високою питомою електропровідністю за допомогою наносекундних розрядів із субнаносекундним фронтом у газових бульбашках є такі режими, коли активний опір оброблюваної рідини становить 10–40 Ом, зосереджена індуктивність розрядного кола під час обробки рідини не перевищує 2 нГн, ємність шару оброблюваної рідини становить 3,6–14 пФ з амплітудою імпульсів від високовольтного низькоомного джерела не менше 30 кВ та частотою імпульсів 1500–2000 імпульсів за секунду. Зі збільшенням активного опору рідини в заданих межах амплітуда напруги на шарі оброблюваної рідини зростає за інших незмінних умов, у тому числі за незмінної амплітуди напруги від джерела. Амплітуда напруги на шарі оброблюваної рідини при такому збільшенні може перевищувати амплітуду напруги від джерела в 1,6 рази, а також перевищувати напругу на реакторі в цілому (послідовне з'єднання об'ємного стримера та шару води) через наявність зосередженої індуктивності в колі розряду, в якій накопичується енергія під час розряду.* ***Наукова новизна.*** *Показано можливість використання наносекундних розрядів із субнаносекундними фронтами в газових бульбашках для енергоефективної дезінфекції рідин, у тому числі з високою питомою електропровідністю. У цьому випадку плазмовий електрод – об'ємний стример – виступає в ролі високовольтного електрода при дезінфекції рідин.* ***Практична значимість****. Отримані результати комп'ютерного моделювання підтверджують можливість промислового застосування наносекундних розрядів із субнаносекундним фронтом для дезінфекції та очищення водовмісних рідин з високою питомою електропровідністю.* Бібл. 23, рис. 13.

Ключові слова: **знезараження води високовольтними імпульсами, розрядний блок, високовольтний стримерний плазмовий електрод, наносекундний розряд у газових бульках у воді, довга електрична лінія, субнаносекундний час наростання високої напруги.**

Introduction. Liquids with high specific electrical conductivity, which exceeds the electrical conductivity of river and tap water, are, for example, seawater, milk. Is it possible to disinfect such liquids using discharges in gas bubbles inside such liquids?

Discharges are permissible in water, unlike in food products, because discharges in food products cause undesirable changes that impair their organoleptic properties. It follows that water can be disinfected and purified using a wider range of factors. This range includes such powerful factors as high-energy electrons and microparticles with high electrochemical potential: OH^- radicals, hydrogen peroxide H_2O_2, ozone O_3, as well as broadband radiation from discharges. However, these factors can be used jointly and effectively only when discharges are carried out inside a volume of water in a gaseous environment, for example, in gas bubbles. This action is fundamentally different from the action that is widely used in the world today, which is provided by ozone technologies. In ozone technologies is used only one active factor from electrical discharges (barrier discharges are most often used) – ozone, which is also not the most effective active factor that can be obtained and usefully used for disinfection and purification of water from discharges.

The most effective can be considered nanosecond discharges, when in a gas volume (for example, in gas bubbles) inside the water, a volumetric streamer is created in a fraction of a nanosecond, which glows and covers the entire gas discharge gap along its length. This is ensuring the presence of a strong electric field in the water itself, contact over the maximum area on the plasma interface surface of the volumetric streamer with water and the transition of active microparticles (electrons, ions, atomic oxygen O, radicals OH^-, hydrogen peroxide H_2O_2, ozone O_3, etc. in the paradigm of de Broglie's theory of matter waves) into the water for its disinfection and purification. It is method minimizes specific energy consumption and the cost of disinfecting water treatment.

The interest in using high-voltage pulses as short as possible for disinfection of water and liquid food products is to reduce the specific energy costs for disinfection and to increase the efficiency of such treatment by increasing the amplitude of the electric field strength in the treated liquid while reducing the duration of the operating high-voltage pulses. For example, magnetic-semiconductor high-voltage generators with nanosecond stream interrupters are known [1, 2]. At present, researches have achieved sub-nanosecond fronts of high-voltage voltage and current pulses with durations from one to several nanoseconds (in the load). They are using both closing and opening switches [3–5]. It is for such pulses that it is possible to obtain a volumetric streamer plasma in the discharge gap without transitioning to a contracted (cord) discharge.

Purpose. The purpose of the work is to determine, using computer modelling, energy-efficient modes of disinfecting treatment of water-containing liquids with high specific electrical conductivity using nanosecond discharges with a subnanosecond front in gas bubbles. More energy-efficient modes are the ones that provide a higher disinfection degree than traditional technologies of high-voltage ozonation of water and air environments, with the same specific energy for disinfection. The efficiency of a high-voltage pulse modes significantly exceeds 70 %, because the installation is based on a Tesla transformer, the efficiency of which exceeds 80 %. The proposed flow-through mode of water disinfection provides specific energy consumption of less than 0.7 kWh/m³.

Electrical diagram and calculating the parameters of a high-voltage pulsed installation discharge circuit, where volumetric nanosecond streamer discharges with a sub-nanosecond front in gas bubbles are possible. The electrical circuit of the experimental installation for water disinfection using discharges in gas bubbles is given in [6]. Figure 1 shows the electrical circuit, with the help of which in this work, the computer simulation in Micro-Cap 12 of the process of processing liquids with high specific electrical conductivity by pulsed electrical discharges in gas bubbles inside the liquid was carried out.

The main high-voltage storage capacity in the diagram (Fig. 1) is designated *C*2. The circuit for simulation was chosen to emphasize the importance of the main high-voltage discharge circuit, namely, *C*2-*SW*1-*L*2-*TD* (long line with input capacitance *C*4 and output capacitance *C*3)-*SW*3-parallel connection *L*1 and *R*1-parallel connection *R*7 and *C*1-*C*2. The letters *SW* denote switches that operate instantly. Elements of the electric circuit: *SW*3-parallel connection *L*1 and *R*1-parallel connection *R*7 and *C*1 simulate the reactor – a series connection of the gas discharge gap (with a transient active resistance *R*1) with the plasma after switching (with the inductance of the plasma volume *L*1) and the liquid layer with the active resistance *R*7 and the capacitance *C*1.

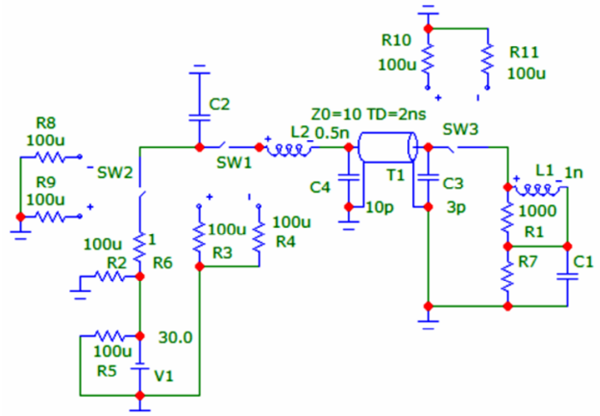

Fig. 1. The electrical circuit diagram used for the computer simulation in this work

The capacitance *C*2 in our calculations we took equal to *C*2=150 pF, which corresponds to the value of *C*2 used in our experiments, or *C*2=1000 pF. The active resistance of the water layer *R*7 we took equal to *R*7=10 Ω or *R*7=40 Ω. In this case, the capacitance *C*1 of the water layer was taken equal to *C*1=14 pF or *C*1=3.6 pF, respectively.

Since the bandwidth of the Rigol DS1102E digital oscilloscope, which we used to measure voltage and current pulses, is 100 MHz, the oscillograms may not transmit the high-frequency component of real pulses. Therefore, computational studies of the capabilities of the electrical circuit of our installation are required. According to [7], we assumed the specific electrical conductivity γ when calculating the resistance $R7 \equiv R_w$ of the liquid layer (see Fig. 1) equal to γ=5 $(\Omega\cdot m)^{-1}$, which approximately corresponds to the specific electrical conductivity of sea water. In the calculations, we did not take into account electrode effects, which can cause a nonlinear dependence of the electrical conductivity [8] of the «water–metal electrodes» system on the applied voltage, because their contribution is minimal when the high-voltage pulses have a voltage amplitude of approximately 30 kV and a duration of less than 50 ns.

If, during a discharge in a gas bubble, we assume the thickness of the water layer for the flow of a pulsed current through the water layer to be $l=5\cdot10^{-3}$ m, and the cross-sectional area *S* of the current flow through the water $S=0.25\cdot10^{-4}$ m^2, then the active resistance of the water layer will be: $R_w=l/(\gamma\,S)=5\cdot10^{-3}/(5\cdot0.25\cdot10^{-4})=40\ \Omega$. The capacitance $C_w=\varepsilon_0\cdot\varepsilon\cdot S/l\approx8.85\cdot10^{-12}\cdot81\cdot0.25\cdot10^{-4}/(5\cdot10^{-3})=3.58\cdot10^{-12}$ F, where ε_0 is the dielectric constant (absolute dielectric permeability of vacuum); ε is the relative dielectric permeability of the medium. At R_w=10 Ω of a volume of water with the same specific electrical conductivity γ=5 $(\Omega\cdot m)^{-1}$, its capacitance will be:

$$C_w=\varepsilon_0\cdot\varepsilon\cdot S/l\approx8.85\cdot10^{-12}\cdot81\cdot0.25\cdot10^{-4}/(5\cdot10^{-3})\approx14\cdot10^{-12}\ \text{F}.$$

We have assumed that the relative dielectric constant of water is a real constant, which is equal to 81.

The time constant τ_w of the discharge of the capacitance C_w of the water volume to the internal resistance R_w of this volume is determined as:

$$\tau_w=R_w\cdot C_w=[l/(\gamma\cdot S)]\cdot\varepsilon_0\cdot\varepsilon\cdot S/l=\varepsilon_0\cdot\varepsilon/\gamma.$$

From this formula it follows that this time constant is determined by the ratio of the dielectric constant (permeability) of water to its specific electrical conductivity and is the smaller, the greater the specific electrical conductivity of water. At γ = 5 $(\Omega\cdot m)^{-1}$ $\tau = 8.85\cdot10^{-12}\cdot81/5\approx1.43\cdot10^{-10}$ s. This means that after the instant disconnection of the external source of high-voltage pulses, the capacitance of this volume of water will be discharged to the active resistance of this volume with a time constant $\tau_w \approx 1.43 \cdot 10^{-10}$ s.

With a capacitance C of the high-voltage pulse source C=150 pF, the time constant τ of its discharge into a resistive load with a resistance R=10 Ω will be $\tau = R \cdot C = 10 \cdot 150 \cdot 10^{-12} = 1.5 \cdot 10^{-9}$ s. It follows from this that the duration of the front (rise time) of the voltage on the load R=10 Ω must be less than 1 ns so that the real maximum voltage on the load is not significantly less than the maximum (possible) voltage on it, to which it can be charged by a pre-charged capacitive source of high-voltage pulses with a capacitance C. If the duration of the front of the pulses on the load is determined mainly by the inductive component, namely $t_f = 2.2 \cdot L/R$, then with L=2 nH and R=10 Ω $t_f = 2.2 \cdot L/R = 2.2 \cdot 2 \cdot 10^{-9}/10 = 4.4 \cdot 10^{-10}$ s = 0.44 ns. Thus, the lumped inductance of the discharge circuit with a load R=10 Ω should not exceed L=2 nH.

We use the formula for the inductances of short conductors to determine approximately the inductance of the volumetric discharge channel in a gas bubble [9]:

$$L = \frac{\mu_0 l}{2\pi} \cdot \left(\ln \frac{2l}{r_c} - \frac{3}{4} + \frac{128 \cdot r_c / 45\pi}{l} - \frac{r_c^2}{4l^2} \right), \quad (1)$$

where l is the length of the discharge channel, and r_c is its radius. At $l = 5 \cdot 10^{-3}$m, $r_c = 2.5 \cdot 10^{-3}$m $L = 2 \cdot 10^{-7} \cdot 5 \cdot 10^{-3}$(ln4–3/4+0.4527–0.0625)≈$10^{-9}$·(1.386–0.75+0.4527–0.0625)≈ ≈$1.03 \cdot 10^{-9}$ H. In Fig. 1, the inductance of the volumetric discharge channel (volume streamer) is denoted by $L1$.

To estimate the resistive phase τ_R of the commutation, we use the empirical formula of J.C. Martin [10, 11]:

$$\tau_R = 88 R^{-\frac{1}{3}} E_0^{-\frac{4}{3}} (\rho / \rho_0)^{\frac{1}{2}}. \quad (2)$$

The dimension of the time constant τ_R of the resistive switching phase (exponential voltage drop) is [ns], for the electric field strength E_0 along the discharge channel near it is 10 kV/cm. The dimension for R – the generator impedance (in our case, this is the active resistance of the water layer in the discharge circuit) is [Ω]; ρ/ρ_0 – the ratio of the density of a gas in a gap to the density of the same gas under normal conditions; in our case ρ/ρ_0=1.

The field strength E_0 at the sharp edge of the end of the high-voltage rod electrode in the gap between the high-voltage rod electrode and the grounded electrode with zero potential opposing it is determined using the evaluation formula [12]:

$$E_0 = \frac{U_0}{r} \left(\ln \frac{2d}{r} \right)^{-1}, \quad (3)$$

where $U_0 \equiv U_c \equiv V$ is high-voltage potential of the rod electrode.

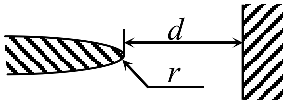

Fig. 2. Electrode system

Figure 2 shows the remaining elements: r – radius of the tip, d – distance from the end of the rod electrode to the plane.

At U_0=50 kV, r=0.1 mm, d=10 mm according to (3) we obtain:

E_0=(50/0.1)/ln(2·10/0.1)≈500/5.3≈94 kV/mm.

At d=5 mm E_0≈500/4.6≈109 kV/mm.

At R=10 Ω, E_0=94 (10 kV/cm)=940 kV/cm, $(\rho/\rho_0)^{1/2}$=1 we get the following result:

$\tau_R = 88 \cdot 10^{-1/3} \cdot 94^{-4/3} = 88 \cdot 0.464 \cdot 0.00237 \approx 0.1$ ns.

At E_0≈109 kV/mm:

$\tau_R = 88 \cdot 10^{-1/3} \cdot 109^{-4/3} = 88 \cdot 0.464 \cdot 0.002 \approx 0.08$ ns.

In Fig. 1, the active resistance of the water layer in the discharge circuit is designated $R7$.

A typical picture of pulsed discharges in a gas bubble inside water and a sketch of the design of a reactor (unit) for disinfecting water in a stream using nanosecond discharges with a subnanosecond front in gas bubbles. Figure 3 shows a typical integral picture (photo) with many pulsed discharges in a gas bubble inside water. We received this photo while conducting our experiments. The image in Fig. 3 can be spectrally analysed, for example, using the methods described in [13].

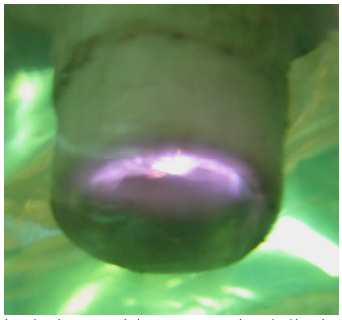

Fig. 3. A typical photo with many pulsed discharges in a gas bubble inside water

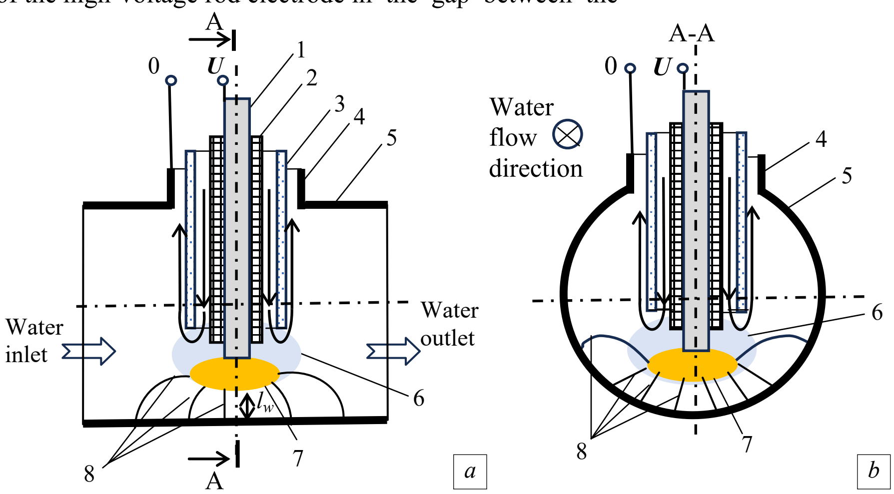

Fig. 4. a – axial longitudinal section of the pipe-reactor with running water; b – cross-section A-A of the pipe-reactor with running water

Figure 4 shows a reactor (unit) design variant for disinfection treatment of water in a stream using nanosecond discharges with a subnanosecond front in gas bubbles in real dimensions. We have used the following notations here. The arrows (→) indicate the direction of gas movement in the reactor; 1 – high-voltage rod electrode under U potential; 2 – the insulation of high-voltage electrode 1; 3 – insulating cylinder to ensure gas movement in water, creation of bubbles in the reactor with flowing water; 4 – metal pipe with zero potential for introducing high-voltage pulses and gas into the reactor through it; 5 – metal reactor pipe with flowing water and gas bubbles in it (water), to which (pipe) pipe 4 is short-circuited; 6 – gas bubble; 7 – volume inside the gas bubble, which is filled with plasma of a pulse discharge in gas (volume streamer or near high-voltage electrode plasma). It (plasma) borders on the water being disinfected. 8 – conventionally depicted electric field lines in water in the zone of the most effective disinfection treatment in the presence of a discharge in a gas bubble. l_w – the minimal distance in water between the plasma high-voltage electrode and the inner surface of the metal reactor pipe (tube). When breakdown pulse voltage in the gas bubble equals 50 kV l_w≈2–5 mm.

Results and discussion. In [14], based on experimental data, the possibility of the existence of a primary volumetric ionization zone during switching of high-voltage dischargers is shown. In [15], the existence of volumetric streamers is shown by calculation. In [16], the possibility of the operation of a high-voltage trigatron in the subnanosecond time range is shown by calculation.

Figure 5 shows the result of our computer modelling of the electric field distribution in the discharge gap (in the reactor) with a gas bubble and a layer of treated water at the time t=1.5 ns after the start of the nanosecond discharge in the gas bubble. It follows from this figure that inside the volumetric streamer between the rod metal high-voltage electrode (in Fig. 5 it is represented by a white figure) and the surface of the water layer the electric field strength does not exceed 25 kV/cm. At the same time, in the water layer near the interface with the plasma of the bulk streamer, the electric field strength reaches 100 kV/cm.

Calculations [15] and experiments [17] have shown that when the duration of the discharge pulse front in a gas bubble is approximately 1–2 ns, a plasma volume (volume streamer) is created in the discharge gap, which covers the entire length of the gap to the water interface. In the process of creating volume streamers runaway electrons play an important role, and in the case of creating negative streamers, the emission of electrons from a high-voltage cathode [18, 19]. The potential of the high-voltage metal electrode, because of the appearance of a plasma formation (a streamer) in the discharge gap, moves by the streamer towards the interface between the gas bubble and water. Inside the streamer, the electric field strength is significantly lower than in water near the water-gas bubble interface. That is, a strong electric field penetrates the water, creating a volume in the water with a strength of more than 40 kV/cm. Thus, in the water layer between the plasma volume high-voltage electrode and the grounded metal electrode, a volume zone of a strong electric field with an intensity of 40 kV/cm to 120 kV/cm is created. In addition, broadband radiation, including ultraviolet and even shorter wavelength radiation, as well as active microparticles, including OH^- radicals, enters the water from the volume streamer, or a volume nanosecond discharge [20]. This set of factors of the combination of high-voltage pulse actions provides a significant reduction in specific energy consumption for disinfecting water treatment compared to traditional ozonation.

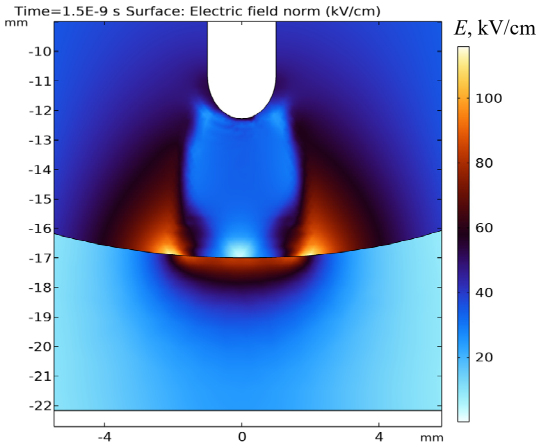

Fig. 5. Distribution of electric field intensity inside reactor

Due to the short length of the discharge pulses (less than 10 ns), they may not change the organoleptic properties of food products, which opens up the possibility of using such short high-voltage discharge pulses for disinfecting food products.

Figure 6 shows the result of calculating of the pulse voltage $V1$ on the reactor (serial connection of the plasma discharge channel in the gas bubble and the water layer) and the pulse voltage $V2$ on the water layer through which the current flows. In this case a capacitance $C2$=150 pF, an active resistance of the water layer R_w=10 Ω and a capacitance of the water layer C_w≈14·10^{-12} F.

With a volumetric discharge channel (volume streamer) in a gas bubble with a channel diameter of approximately 5 mm and a length of 5 mm, it is possible to achieve a channel inductance of 1 nH [9]. Then, it is possible to obtain voltage pulses with an amplitude of up to 28 kV. It is possible if the amplitude of the pulse voltage from the pulse generator is 30 kV, in a reactor with a volumetric discharge channel in an air bubble 5 mm long and a water layer 5 mm thick, which is connected in series with the discharge volumetric streamer. Then the amplitude of the voltage pulses will be 25.2 kV in the water layer (see Fig. 6).

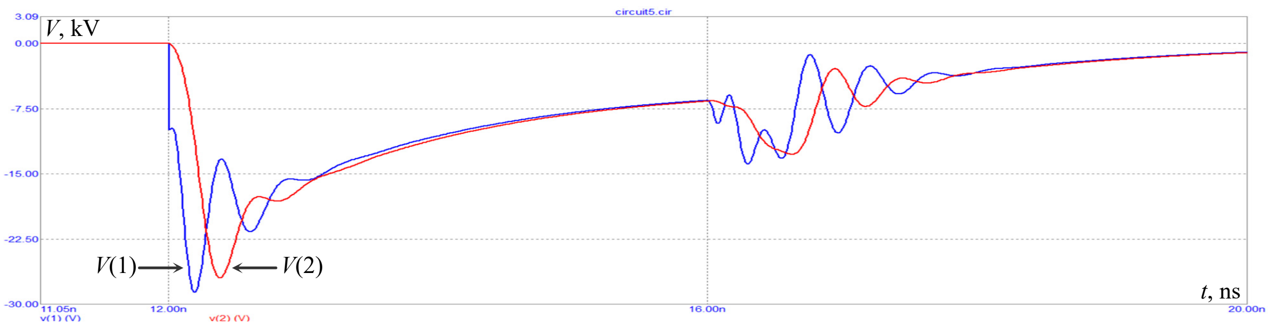

Fig. 6. The result of the calculation (according to the scheme in Fig. 1) of the pulse voltage $V(1)$ on the reactor voltage and $V(2)$ on the water layer at $C2$=150 pF, $C1$=14 pF, R_w=10 Ω. The long TD line is taken into account

The wave impedance of the long line should be made small (approximately 10 Ω), because with an increase in the wave impedance of the long line, the amplitude of the pulse voltage on the water layer decreases. As can be seen from Fig. 6, the calculated pulse duration on the load – a reactor with a discharge in a gas bubble and a water layer – is in the considered case approximately 1.5 ns at half-wavelength, and the pulse front duration on the water layer is ≈0.4 ns.

Figure 7 presents the result of calculating the pulse voltage *V*(1) on the reactor (serial connection of the plasma discharge channel in the gas bubble and the water layer) and the pulse voltage *V*(2) on the water layer. This is in the case when the circuit on Fig. 1 does not have a long *TD* line, and the high-voltage outputs (terminals) of the capacitors *C*3 and *C*4 are short-circuited, *R*7=10 Ω, *C*1=14 pF, *C*2=150 pF. Compared to the option when the presence of a long *TD* line is taken into account (Fig. 6), the time dependence of *V*(1) and *V*(2) has a more oscillatory nature, and the amplitude of *V*(2) and *V*(2) is a little more.

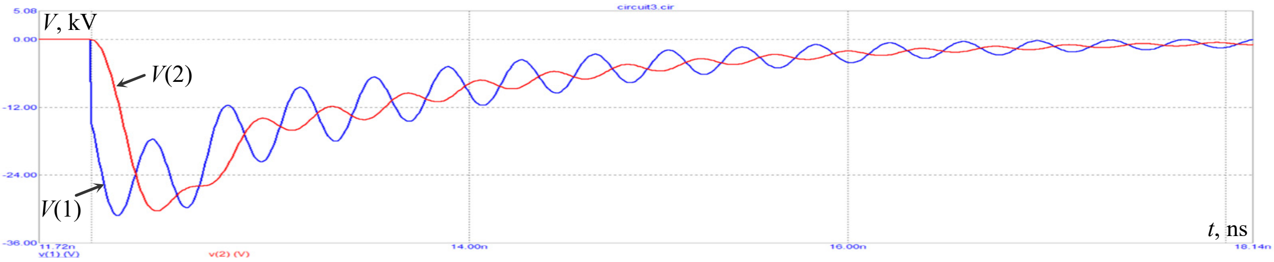

Fig. 7. The result of the calculation (according to the scheme in Fig. 1) of the pulse voltage *V*(1) on the reactor voltage and voltage *V*(2) on the water layer at *C*2=150 pF, *C*1=14 pF, R_w=10 Ω. The long *TD* line is not taken into account

Creating a technologically advanced installation for the disinfection treatment of liquids with high specific electrical conductivity up to γ=5 (Ω·m)$^{-1}$ using discharges in gas bubbles is a complex scientific and technical problem, but one that can be solved right now.

Figure 8 shows the result of calculating the pulse voltage *V*(1) on the reactor (serial connection of the plasma discharge channel in the gas bubble and the water layer) and the pulse voltage *V*(2) on the water layer through which the current flows. In this case the active resistance of the water layer R_w= 40 Ω and the capacitance of the water layer C_w≈3.6·10^{-12} F according to the scheme in Fig. 1. It can be seen that in this case the amplitude of the voltage *V*(2) on the water layer exceeds the voltage from the pulse source by approximately 1.5 times, and the amplitude of the voltage *V*(1) on the reactor as a whole exceeds the voltage from the pulse source by approximately 1.3 times.

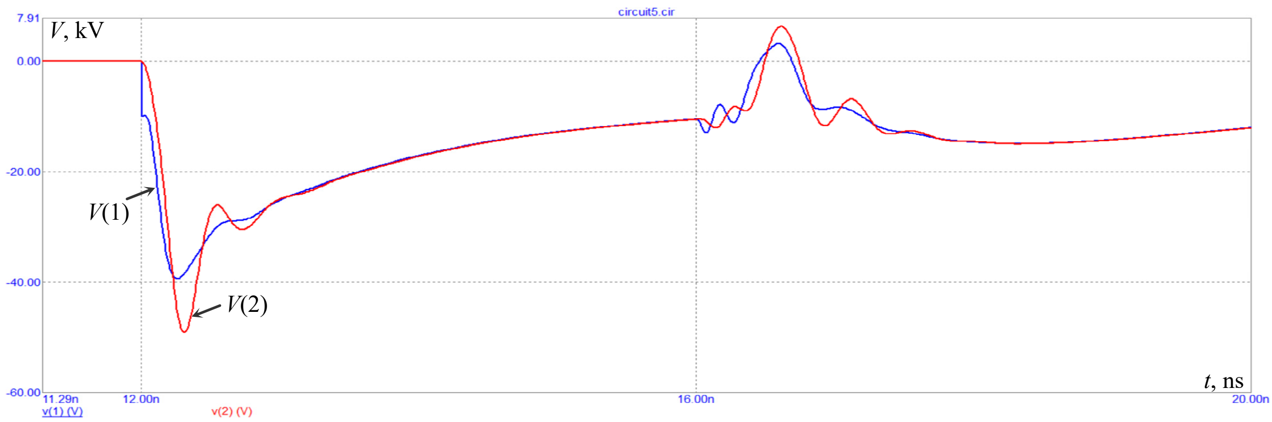

Fig. 8. The result of the calculation (according to the scheme in Fig. 1) of the pulse voltage *V*(1) on the reactor voltage and *V*(2) on the water layer at *C*2=150 pF, *C*1= C_w≈3.6 pF, R_w=40 Ω. The long *TD* line is taken into account

Figure 9 shows the result of calculating the pulse voltage *V*(1) on the reactor (serial connection of the plasma discharge channel in the gas bubble and the water layer) and the pulse voltage *V*(2) on the water layer. This is in the case when the circuit on Fig. 1 does not have a long line *TD*, and the high-voltage terminals of the capacitors *C*3 and *C*4 are short-circuited together, *R*7=40 Ω, *C*1=3.6 pF. Compared to the option when the presence of a long line *TD* is taken into account (Fig. 8), the time dependence of *V*(1) and *V*(2) has a more oscillatory nature, the amplitudes of *V*(1) and *V*(2) are almost the same (as in Fig. 8), there is no reflection from the ends of the long line.

Figure 10 shows the result of calculating the pulse voltage *V*(1) on the reactor (serial connection of the plasma discharge channel in the gas bubble and the water layer) and the pulse voltage *V*(2) on the water layer. This is at *C*2=1000 pF, *C*1=3.6 pF, *R*7=40 Ω.

Figure 11 shows the initial part of the same pulse. These figures show the results taking into account the presence of a long line in the circuit in Fig. 1.

It follows from Fig. 10, 11 that the amplitude of *V*(2) on the water layer is slightly larger than at *C*2=150 pF (other conditions being equal).

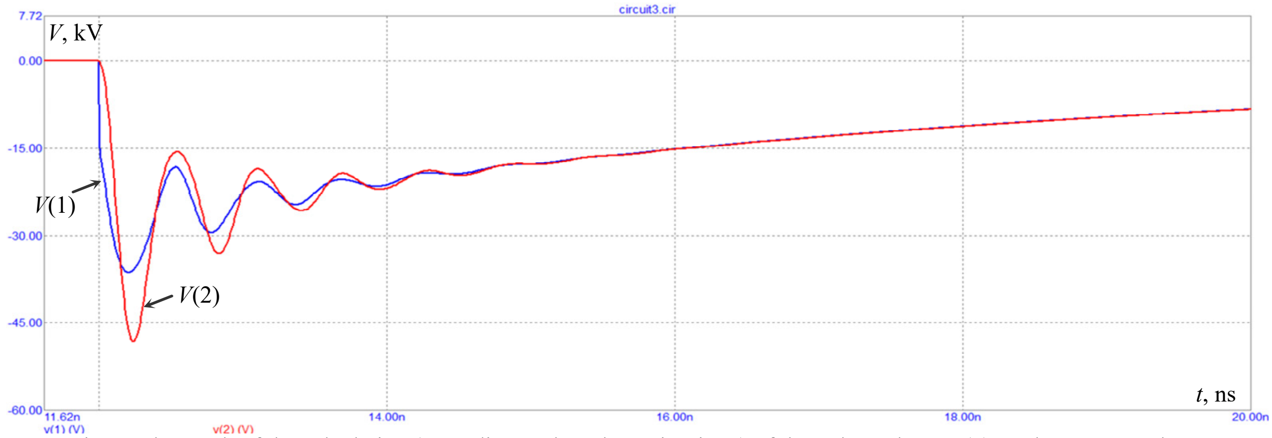

Fig. 9. The result of the calculation (according to the scheme in Fig. 1) of the pulse voltage $V(1)$ on the reactor voltage and $V(2)$ on the water layer at $C2$=150 pF, $C1$= C_w≈3.6 pF, R_w=40 Ω. The long *TD* line is not taken into account

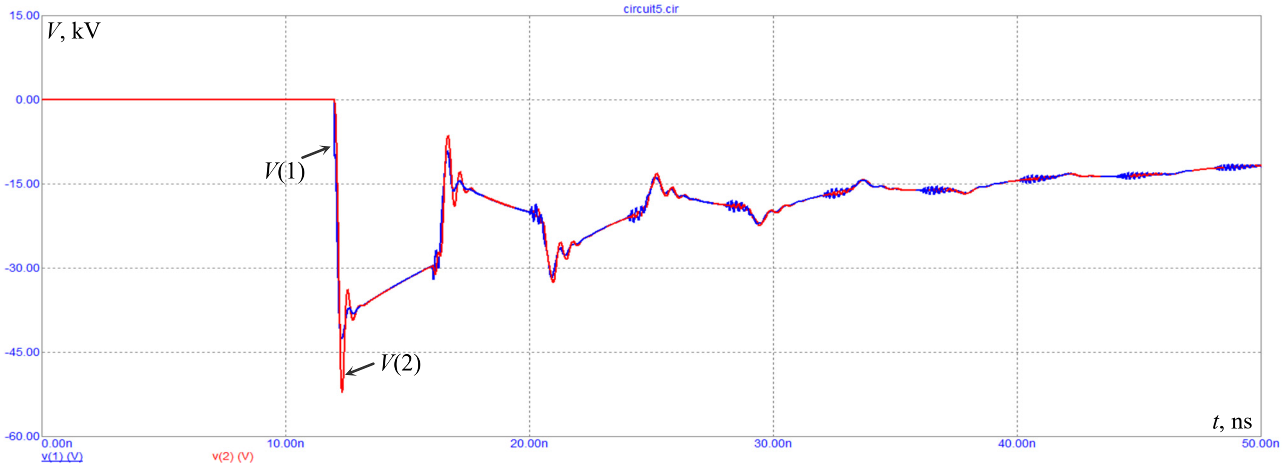

Fig. 10. The result of the calculation (according to the scheme in Fig. 1) of the pulse voltage $V(1)$ on the reactor voltage and $V(2)$ on the water layer at $C2$=1000 pF, $C1$= C_w≈3.6 pF, R_w=40 Ω. The long *TD* line is taken into account

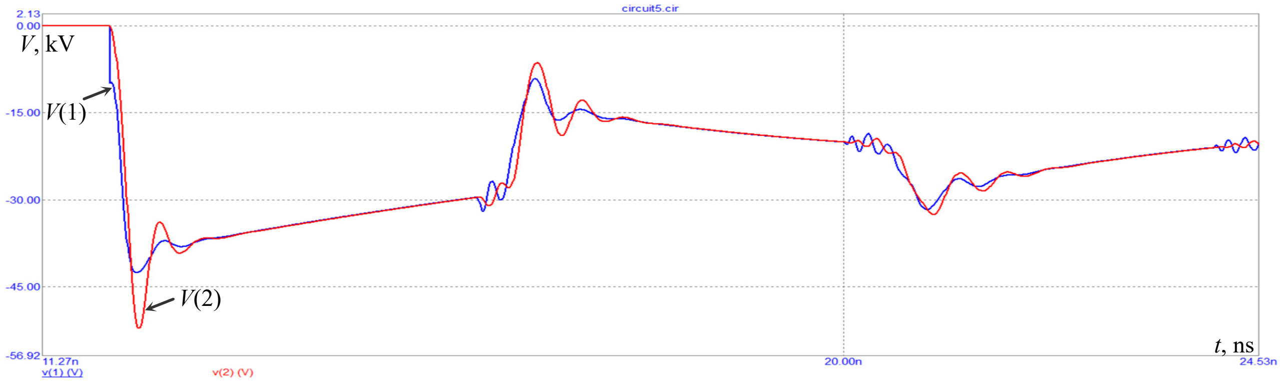

Fig. 11. The initial part of the pulses from Fig. 10

Figure 12 shows the result of the calculation (according to the scheme in Fig. 1) of the pulse voltage $V(1)$ on the reactor (serial connection of the plasma discharge channel in the gas bubble and the water layer). It shows also the pulse voltage $V(2)$ on the water layer at $C2$=1000 pF, $C1$=14 pF, $R7$=10 Ω, and Fig. 13 shows the initial part of the same pulse.

The emergence of a volume streamer in the discharge gap of the reactor and, as a consequence, subnanosecond volume avalanche-streamer switching are possible only at voltage rise rates in the discharge gap on the gas bubble of the order of 10^{14} V/s (3×10^{13}–10^{14} V/s) [16, 21]. To achieve such a rise rate at a breakdown voltage of 50 kV, the time required for the voltage rise on the gas bubble to breakdown is of the order of $5\cdot10^{4}$V/($3\cdot10^{13}$–10^{14} V/s)≈($5\cdot10^{-10}$ –$1.7\cdot10^{-9}$) s. This is a very short, but already achieved switching time of high-voltage switches [17, 21, 22].

The question of the possibility of using short discharge pulses in gas bubbles, when the high-voltage electrode in contact with the processed liquid is plasma (in the form of a volumetric streamer), for the processing of liquid and flowing food products remains open. Appropriate experimental studies are needed. It is not clear whether any chemical and biochemical reactions take place during processing with nanosecond pulses. It is necessary to find out, if such reactions take place, what exactly the reactions are processing during such, and what the final products of such reactions are. Will the organoleptic properties of liquid food products change during such processing with nanosecond pulses with sub-nanosecond fronts?

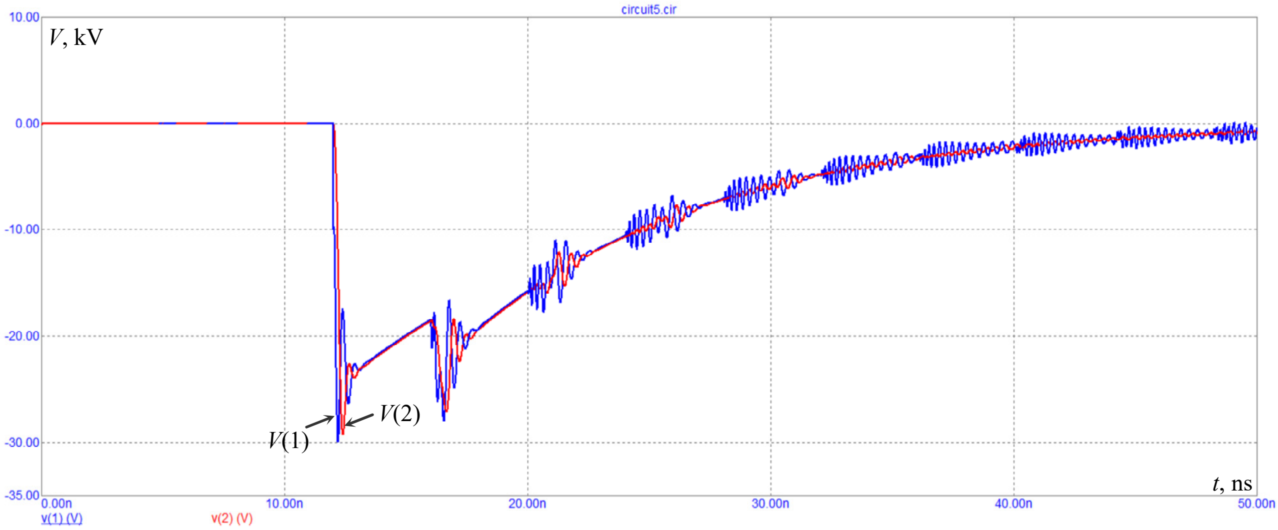

Fig. 12. The result of the calculation (according to the scheme in Fig. 1) of the pulse voltage $V(1)$ on the reactor voltage and $V(2)$ on the water layer at $C2$=1000 pF, $C1$=14 pF, $R7$=10 Ω. The long *TD* line is taken into account

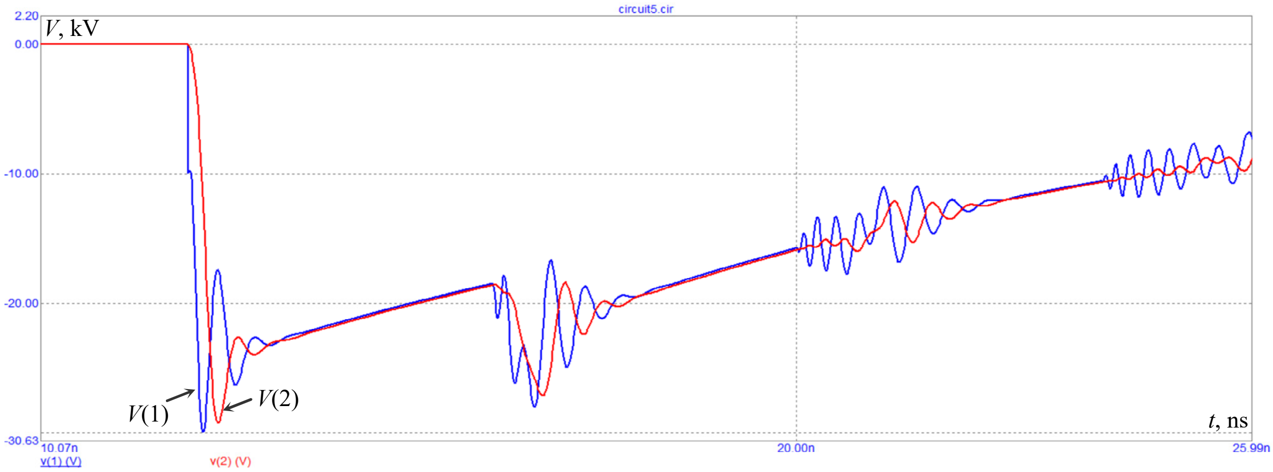

Fig. 13. The initial part of the pulses from Fig. 12

From the analysis of the above calculated results, previously obtained experimental results and results of other authors (including the results presented in [23]), we can conclude that the energy-efficient modes of disinfecting treatment of water-containing liquids with high specific electrical conductivity using nanosecond discharges with a subnanosecond front in gas bubbles are the following modes. Namely, these are modes when the active resistance of the treated liquid in one reactor in one discharge circuit is 10–40 Ω, the lumped inductance of the discharge circuit during liquid treatment does not exceed 2 nH. Add, such modes use the capacitance of the treated liquid layer is 3.6–14 pF with an amplitude of pulses from a high-voltage low-resistance source of at least 30 kV, and a frequency of passing pulses is 1500–2000 pulses per second. When the active resistance of the liquid increases within the specified limits, the voltage amplitude on the layer of the processed liquid increases under other constant conditions, including at a constant voltage amplitude from the source. The voltage amplitude on the layer of the processed liquid with such an increase can exceed the voltage amplitude from the source by 1.6 times. It also exceeds the voltage at the whole reactor (the series connection of the volumetric streamer and the water layer) because of the presence of concentrated inductance in the discharge circuit, where (in the inductance) energy is stored during discharge.

Conclusions.

1. The possibility of obtaining nanosecond high-voltage pulses (with volumetric streamers in gas bubbles inside water) with subnanosecond fronts in reactors for the disinfection treatment of liquids with high specific electrical conductivity up to 5 S/m=5 $(\Omega\cdot m)^{-1}$ has been shown. Such pulses can provide a higher disinfection degree at lower specific energy consumption than longer pulses, because of the lower energy in each pulse and the higher amplitude of the electric field strength in the treated liquid. Experiments that we have already conducted have shown that nanosecond pulses provide a higher disinfection degree at lower specific energy consumption than microsecond pulses [6]. Therefore, further reduction of pulse duration and duration of their fronts is promising. In addition, such short pulses with a subnanosecond front ensure the presence of volumetric plasma formations – volumetric streamers, as an extension of a metal high-voltage electrode. These plasma formations provide an additional disinfection effect on the liquid being treated by supplying it with active microparticles and broadband radiation, including ultraviolet and even shorter-wave radiation.

2. Experimental results obtained by various researchers, including the authors of this material, confirm the possibility of obtaining volumetric pulse discharges in gas environments (mediums) at atmospheric pressure.

3. An example of a sketch of the design of a liquid processing unit in the flow mode is given, when as a result of a pulse discharge in a gas bubble, a volumetric streamer (volumetric plasma electrode) is created. This plasma electrode is an extension of a high-voltage metal electrode and creates a volumetric zone of the most effective decontamination treatment in the treated liquid with an electric field strength that can reach 100 kV/cm and more.

4. Using computer modelling, energy-efficient modes of decontamination treatment of water-containing liquids with high specific electrical conductivity using nanosecond discharges with a subnanosecond front in gas bubbles are determined. These are such modes when the active resistance of the liquid being processed is 10–40 Ω, the lumped inductance of the discharge circuit during liquid processing does not exceed 2 nH. At the same time, the capacitance of the layer of the liquid being processed is 3.6–14 pF with amplitude of pulses from a high-voltage low-resistance source of at least 30 kV and a pulse frequency of 1500–2000 pulses per second.

Conflict of interest. The authors declare that they have no conflicts of interest.

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M.I. Boiko[1], *Doctor of Technical Sciences, Professor,*
A.V. Makogon[2], *PhD, Senior Researcher,*
[1] National Technical University «Kharkiv Polytechnic Institute»,
2, Kyrpychova Str., Kharkiv, 61002, Ukraine,
e-mail: qnaboyg@gmail.com (Corresponding Author)
[2] Institute of Electrophysics & Radiation Technologies
National Academy of Sciences of Ukraine,
28, Chernyshevsky Str., Kharkiv, 61002, Ukraine,
e-mail: artemmak1991@gmail.com

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