ENERGY EFFICIENCY OF THE DISINFECTION TREATMENT OF LIQUID FOODSTUFFS BY HIGH-VOLTAGE PULSE EFFECTS

Purpose. Experimentally determine the rational modes and energy efficiency of decontamination treatment of flowing food products using high-voltage impulse actions in comparison with traditional pasteurization. Methodology. We used pulse generation method with the help of a step-up transformer, high-voltage pulse capacitors and spark gaps with a system of peaking of pulse front to obtain high-voltage pulses in working chambers - the generator load. The pulses on the load were measured by a low-resistance resistive voltage divider, were transmitted over a broadband coaxial cable and recorded using an analog CS-12 oscilloscope or a Rigol DS1102E digital oscilloscope with a bandwidth of 100 MHz for each. The working chambers were filled with water, milk or milk whey and consisted of an annular hull made of PTFE and metal electrodes forming the bottom and the chamber cover having flat linings of food grade stainless steel for contact with the food product inside the chamber. Results. We obtained high-voltage pulses on the generator load with a base duration of 300 to 1200 ns at pulse repetition rates up to 500 pulses per second. We obtained experimentally the amplitude of the voltage pulses on the generator load up to 75 kV, and the electric field strength up to 35 kV/cm in working chambers with a gap of 22 mm and up to 50 kV/cm in working chambers with a gap of 15 mm. These characteristics of the pulses allowed complete and irreversible inactivation of microorganisms in food liquids in working chambers. Originality. We showed that there are modes of treatment food products with the help of high-voltage pulse actions, which allow better to preserve the biological and nutritional value of the products in comparison with heat treatment with their complete disinfection and at a significantly lower specific energy consumption. Practical value. The experimental regimes for treating milk, whey and water with reduced specific energy consumption open the prospect of industrial application of a complex of high-voltage pulse actions for the disinfecting treatment of water-containing food products.

References 7, tables 3, figures 10.

Key words: generator of high-voltage pulses, transformer, capacitor, multi-gap discharger, multichannel switch, working chamber, disinfecting food treatment.

Introduction. Traditional thermal methods of disinfecting treatment (pasteurization and thermal sterilization) of liquid food products, wine materials, beverages are energy-consuming and do not allow to preserve their initial biological and nutritional value to a sufficient extent [1, 2]. One of the most promising ways of non-thermal disinfection treatment of products is the way of processing by means of a complex of high-voltage impulse actions (CHVIA). The English-language scientific literature uses the term PEF-treatment (PEF – pulsed electric field, treatment with a pulsed electric field). Most liquid food products are water-containing. Therefore, the important question is also about rational modes of decontaminating water treatment by using CHVIA.

The goal of the work is to experimentally determine the rational modes and energy efficiency of decontaminating treatment of liquid food products by means of high-voltage impulse actions in comparison with traditional pasteurization.

Experimental installation. To carry out experimental studies, we used a facility, which was first...
described in [3]. The electrical circuit of the installation with the control system is shown in Fig. 1.

The installation consists of low-voltage and high-voltage parts. The high-voltage part consists of a generator of high-voltage pulses and a load – a working chamber WCH. The generator contains a start cascade (C1, DC1) and two cascades of sharpening (C2, DC2 and C3, DC3). Each cascade contains a capacitor and a discharger. The discharger DC1 of the start cascade is multi-gap. All arresters are multi-channel. In the simplest mode of operation, only the first cascade is used. The disadvantage of this mode is the insufficient steepness of the pulse front on the load – the WCH working chamber. Therefore, the main amount of the experiments was carried out using all three cascades.

After connecting to a three-phase power supply, during flow processing, pressing the button SB1 starts the pump electric motor M which pumps the processed product through the WCH working chamber. Pressing the button SB3 energizes the relay K2, its contacts K2.1, K2.2, K2.3 are closed, and the phase voltage of the power network through the filter L0 - C0 is fed to the primary (low-voltage) winding of the transformer Tr starting the installation. As a result, on the load – the WCH working chamber, pulses are formed of high voltage (up to 120 kV) and current of both polarities with repetition frequency up to 500 pulses. The button SB4 switches off the supply of voltage to the filter L0 - C0 and to the primary winding of the transformer Tr. By pressing the button SB2, the pump electric motor M is switched off.

**Working chambers.** The working chambers (WCH) which are the load for the CHVIA installation are divided into stationary and flowing. In stationary chambers, portions of the product are replaced manually, and in flow chambers through the flow through the chamber which provides the pump and a pumping system. The latter contains containers for feeding and receiving the treated liquid product and hoses. It is in the WCH that energy is released which is initially stored in the main high-voltage capacitor of the installation.

Typical stationary and flow chambers are shown in Fig. 2 and Fig. 3, respectively.

![Fig. 1. Electrical circuit of the CHVIA installation with a control system](image)

![Fig. 2. Variant of stationary WCH with cover – electrode located near](image)

![Fig. 3. a - variant of the design of the flowing technological WCH: 1, 2 – electrodes, 3 – internal volume of the chamber, 4 – dielectric housing; b – WCH](image)
Experimental studies of CHVIA methods for the treatment (PEF-treatment) of food products and water treatment. We experimentally investigated the effect of CHVIA treatment on microbiological contamination, sanitary and hygienic properties and organoleptic parameters of milk, milk whey and water. The investigations were carried out in different treatment modes in stationary and flowing WCHs at the CHVIA installation described above.

A photo of an operating CHVIA installation during the experiments is shown in Fig. 4. The product to be processed was poured into a WCH which was previously sterilized with an alcohol burner, and the chamber was closed with a sterilized lid. Two types of cameras were used: with an interelectrode gap (the distance between the disk cover of the chamber and its bottom) of 15 mm and with an interelectrode gap of 22 mm. We varied the treatment time from 10 s to 30 s. Fig. 5 shows a WCH with an interelectrode gap of 22 mm.

To measure the characteristics of pulses on the load of the CHVIA installation - the working chamber, a resistive low-resistance voltage divider with a division coefficient $k_d=1000$ was used. As the recording device an analog storage oscilloscope C8-12 with a bandwidth of 100 MHz and a digital oscilloscope RIGOL DS1102E with a bandwidth of 100 MHz were used.

To protect against electromagnetic interference, the oscilloscope was located in a shielding cabin with a door screened circuit along the contour. The signal from the low-voltage arm of the voltage divider to the oscilloscope in the measuring cabinet was fed using a coaxial cable with a double braid. The door in the measuring cabinet can be opened and closed tightly both from the outside and from the inside.

Fig. 4. Photo of operating CHVIA installation

Fig. 5. Working chamber with an interelectrode gap of 22 mm:

- $a$ – body made of fluoroplastic,
- $b$ – cover,
- $c$ – interelectrode gap of 22 mm,
- $d$ – cover near the chamber
The inactivating effect of CHVIA on various milk products (milk, whey, yogurt), as well as water, was investigated. To do this, our colleagues, co-executors from the National University of Food Technologies (NUFT), the city of Kiev, prepared water for experiments. They took water «Sofia Kiev» and infested it with bacteria of the \textit{E-coli} group. At each treatment mode of all the fluids studied, three repetitions were performed.

The values of the interelectrode gap in the spark dischargers had the following values: for a multi-gap discharger (MGD), the value of an individual gap is approximately 5 mm, for the first sharpening discharger approximately 20 mm, for a second sharpening discharger approximately 20 mm. At the same time, the number of gaps involved in the MGD was from 4 to 7 inclusive.

The treatment of samples of liquid products and water in the WCH in all modes was carried out by pulses of both polarities. During the period of 20 ms of the AC network voltage during the half-period of the positive voltage of 10 ms, approximately 4 pulses of the same polarity were applied to the WCH, and about 4 pulses of a different polarity were applied to the WCH during the half-period of the negative voltage of 10 ms.

Results of experimental studies of the methods of CHVIA treatment (PEF-treatment). Fig. 6 shows an oscillogram of pulses on the WCH with milk at 7 ruptured gaps of 8 in a multi-gap discharger – MGD without the influence of electromagnetic interference and with a clearly visible pulse front.

![Fig. 6. Typical oscillogram of the voltage pulse on the WCH with raw milk. The scale division along the time axis is 50 ns/div; along the axis of the process is 20 kV/div. In multi-gap discharger 7 gaps of 8 are ruptured. The gap in the WCH is \(d = 22\) mm.](image)

It follows from the oscillogram that the pulse front duration in milk is about 20 ns and the pulse duration along the base before passing through zero is about 300 ns. Amplitude of the voltage pulse is not less than 60 kV. From this it follows that the amplitude of the electric field strength in milk is 60/2.2=27.3 kV/cm. It is also important that in milk which has a resistivity less than tap water or table water, the pulse shape is slightly oscillatory.

Fig. 7 shows a typical oscillogram of the pulse voltage on the WCH with water, contaminated with \textit{E-coli}. The oscillogram was obtained using a digital oscilloscope Rigol 1102 E.

![Fig. 7. Typical oscillogram of the voltage pulse on a working chamber with water «Sofia Kiev» seeded by \textit{E-coli}. The scale division along the time axis is 200 ns/div; along the axis of the process is 20 kV/div. In the multi-gap discharger 6 gaps of 8 are ruptured. The gap in the WCH is \(d = 22\) mm. A low-resistance resistive voltage divider with division coefficient \(k_d \approx 2000\) is used.](image)

Two additional bursts at the fall of the pulse on this oscillogram, as well as on other oscillograms, are due to the presence of three high-voltage capacitive storage devices: the main one and two sharpening ones. The front part of the pulse is due to the last (second) sharpening cascade with the second sharpening capacitive storage, the first additional burst at the pulse decay is due to the presence of the first cascade of sharpening with the first sharpening capacitive storage, and the second additional surge at the pulse decay is due to the presence of the main high-voltage capacitive storage device.

The results of microbiological analyzes of water are given in Table 1.

<table>
<thead>
<tr>
<th>The name of the indicator (units of measure CFU/cm(^3))</th>
<th>Results of investigations, CFU/cm(^3)</th>
<th>Approximated treatment mode, ((E, kV/cm))</th>
<th>Calculated treatment mode, ((E, kV/cm))</th>
<th>Treatment duration ((t, s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water sterile. Dilution \textit{E-coli} (10^6)</td>
<td>210</td>
<td>30</td>
<td>20.09</td>
<td>10</td>
</tr>
<tr>
<td>Water sterile. Dilution \textit{E-coli} (10^8)</td>
<td>0</td>
<td>30</td>
<td>31.8</td>
<td>20</td>
</tr>
<tr>
<td>Water sterile. Dilution \textit{E-coli} (10^8)</td>
<td>60</td>
<td>30</td>
<td>19.0</td>
<td>10</td>
</tr>
<tr>
<td>Water sterile. Dilution \textit{E-coli} (10^8)</td>
<td>0</td>
<td>30</td>
<td>1.8</td>
<td>20</td>
</tr>
</tbody>
</table>

*Note: CFU – colony forming units.*
Fig. 8 shows a typical oscillogram of pulse voltage on the WCH with milk whey.

The pulse duration along the base on the oscillogram (Fig. 8) is approximately 350 ns. The pulse shape is oscillatory with a large decrement of oscillations. The amplitude of the voltage pulse on this oscillogram is approximately 45 kV, and the amplitude of the electric field strength is approximately 20.45 kV/cm.

In Fig. 9 shows a typical oscillogram of the pulse voltage on the WCH with raw milk.

The results of microbiological analyzes of milk whey treated with CHVIA pulses, a sample oscillogram of which is presented in Fig. 8, are given in Table 2-5.

Table 2

<table>
<thead>
<tr>
<th>The name of the indicator, units of measure</th>
<th>CFU/cm³</th>
<th>Result, CFU/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.coli family bacteria in milk whey after CHVIA treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at E≈30 kV/cm, total treatment duration t=10 s and dilution 10⁶</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>at E≈30 kV/cm, total treatment duration t=20 s and dilution 10⁶</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>at E≈30 kV/cm, total treatment duration t=10 s and dilution 10⁸</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>at E≈30 kV/cm, total treatment duration t=20 s and dilution 10⁸</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>The name of the indicator, units of measure</th>
<th>ND for testing techniques</th>
<th>Investigation result</th>
<th>Indicator value in accordance with ND</th>
<th>Compliance with ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determination of the mass portion of vitamin C by titrimetric method in food products</td>
<td>mass part of vitamin C, ppm</td>
<td>ND for testing techniques</td>
<td>Investigation result</td>
<td>Indicator value in accordance with ND</td>
</tr>
<tr>
<td>Determination of peroxidase by the method of qualitative analysis in food products</td>
<td>peroxidase for baked, ultra-pasteurized, sterilized milk</td>
<td>DSTU 7380:2013</td>
<td>detected</td>
<td>absent</td>
</tr>
<tr>
<td>Determination of phosphatase of milk and milk products by method of qualitative analysis</td>
<td>phosphatase for pasteurized milk</td>
<td>DSTU 7380:2013</td>
<td>not detected</td>
<td>absent</td>
</tr>
</tbody>
</table>

From Table 2 it follows that after complete treatment of milk whey in the WCH during 20 s by high-voltage pulses (see Fig. 8) complete inactivation of E.coli bacteria is guaranteed. When treated during 10 s from 20 to 30 colony forming units remain not inactivated. Thus, the existence of a mode of complete guaranteed inactivation at CHVIA treatment of products was confirmed experimentally. In control (not treated by CHVIA) samples of milk whey, a continuous growth of E.coli bacteria (>>1000 CFU/cm³) was observed.
From the results given in Table 6 it follows that in CHVIA treated milk there is a peroxidase enzyme, the absence of which is characteristic of baked, ultrapasteurized, sterilized milk, that is, milk that was amenable to processing at high temperatures (greater than 100 °C). However, in CHVIA treated milk, no enzyme phosphatase was detected, the absence of which is characteristic of pasteurized milk. In addition, from the data of Table 6 it follows that the amount of vitamin C which is very sensitive to different treatments, after CHVIA treatment has remained at the level meeting the requirements of normative documentation (ND), that is, CHVIA treatment is soft processing. All analyzes (microbiological and sanitary-hygienic) of treated and control samples of water-containing foods and water were conducted by specialists of the public utility «Sanepidservice» (public unity «SES», the Kharkiv city). This enterprise is accredited by the National Agency of Ukraine for Accreditation (Accreditation Certificate No. 2H1207 of 25.02.2015).

Energy efficiency of high-voltage prototype of CHVIA installation. Energy efficiency is determined by two components: high degree of microbiological (microbial) disinfection of the processed product at a given specific energy input and reduced specific energy consumption in comparison with known methods (for example, thermal sterilization and pasteurization). The first component can be estimated by conducting CHVIA processing and making the corresponding microbiological analyzes of the processed product (water, milk, milk whey). The second component of energy efficiency can be estimated on the basis of what part of the energy consumed from the network dissipates in total, efficiency of the installation can be estimated as 0.9, or 90% [4-6]. It is more difficult to estimate how much energy is dissipated in the chamber, in this case filled with water (see Fig. 1). The first (largest) peak after the pulse front is the maximum voltage on the WCH due to the energy input to the chamber from the most low-inductive discharge circuit with the capacitive storage C3. The second peak corresponds to the process of connecting and discharging capacitor C2 on the WCH. The third peak corresponds to the process of connecting to the discharge on the WCH of capacitance C1, more remote from the WCH and having the greatest inductance.

Energy which is released in the WCH during processing can be estimated by the formula

\[ E = nT \int uav dt = nT_{av}u_{av}t, \]

where \( i \) is the current as a temporal function, \( u \) is the voltage as a temporal function, \( i_{av} \) is the averaged current, \( u_{av} \) is the averaged voltage, \( t \) is the duration of one pulse at half-height – the length of time during which the energy of the pulse is released in the WCH, \( n \) is the pulse repetition rate, \( T \) is the treatment duration.

We suppose that water in the WCH is a purely resistive load. The pulse duration is determined from the oscillogram in Fig. 10. Thus

\[ R_{wch} = (\tau/0.7)/C_{hv}, \]

where \( \tau \) is the pulse duration at half-height, and \( \tau/0.7 \) is the pulse duration before the measured value decreases from the amplitude value in \( e \approx 2.71828 \) time.

For our installation \( C_{hv} \approx 10^{-8} \text{ F}, \ t \approx 380 \text{ ns} \) (see oscillogram in Fig. 10). Thus

\[ R_{wch} = (\tau/0.7)/C_{hv} = (3.8 \times 10^{-7}/0.7)/10^{-8} = 54.3 \Omega. \]

Taking into account that \( u_{av} \approx 40 \text{ kV}, \ i_{av} = u_{av}/R_{wch} = 40000 \text{ V}/54.3 \Omega \approx 736.65 \text{ A}. \) From here it follows that at

\[ n = 400 \text{ pulses/s}, \ T = 10 \text{ s}, \ t = 3.8 \times 10^{-7} \text{ s}, \] the energy \( E_{wch} \) dissipated in the chamber is

\[ E_{wch} = nT_{av}u_{av}t = 400 \text{ pulses/s} \times 10 \text{ s} \times 736.65 \text{ A} \times 40000 \text{ V} \times 3.8 \times 10^{-7} \text{ s} = 16 \times 736.65 \times 3.8 \approx 44.8 \text{ kJ}. \]

Here, the averaged power \( P \) consumed in the WCH with water approximately equals \( P = E_{wch}/T = 44.8 \text{ kJ}/10 \text{ s} \approx 4.5 \text{ kW}. \)

The energy \( E_{1C1} \) initially stored in the high-voltage discharge circuit in the capacitor C1 before each discharge can be estimated by the formula

\[ E_{1C1} = C1 u_{C1}^2/2 \approx 10^{-8}(50 \times 10)^2/2 = 12.5 \text{ J}. \]

We estimate the total energy \( E_{CI} \) accumulated in C1 during time \( T \)

\[ E_{CI} = nTE_{CI} = 400 \text{ pulses/s} \times 10 \text{ s} \times 12.5 \text{ J} = 50000 \text{ J} = 50 \text{ kJ}. \]

\[ E/E_{CI} \approx 44.8/50 = 0.896. \]

The resistivity of the water in WCH can be estimated by the formula

\[ \rho = R_{wch} \times S/l, \]

where \( S \) and \( l \) are the cross-sectional area and length of the chamber, respectively.
where $S$ is the cross-sectional area of WCH with the liquid to be treated relative to the current flow direction, $l$ is the length of the interelectrode gap in the WCH i.e. its (working chamber’s) height.

At $S = 3.14 \cdot 4.75^2 \cdot 10^{-4} = 7.1 \cdot 10^{-3} \text{ m}^2$, $l = 1.5 \cdot 10^{-2} \text{ m}$:

$\rho = 54.3 \Omega \cdot 7.1 \times 10^{-3} \text{ m}^2/1.5 \cdot 10^{-2} \text{ m} = 25.7 \Omega \cdot \text{m}.$

We estimate the heating $\Delta t$ of water in a non-current (stationary) WCH for $T = 10$ s with energy $E \approx 44.8 \text{ kJ}$ dissipated in the chamber. If we assume that half of this energy was used to heating the water, and the other half to heating the metal electrodes - the covers of the WCH and its insulating (fluoroplastic) housing, then

$$E = 2 \cdot c \cdot V \cdot Y \cdot \Delta t,$$

where $c = 4200 \text{ J/(kg·K)}$ is the specific heat of water, $V$ is the water volume in the WCH, $Y = 10^3 \text{ kg/m}^3$ is the density of water.

$$V = S \cdot l = 7.1 \cdot 10^{-3} \text{ m}^2 \cdot 1.5 \cdot 10^{-2} \text{ m} \approx 10^{-4} \text{ m}^3.$$

So:

$$\Delta t = 0.5 \cdot 44.8 \cdot 10^{-3} \text{ J/(4200 J/(kg·K))} \times \times 10^{-4} \text{ m}^3 \cdot 10^3 \text{ kg/m}^3 = 53.3 \text{ K}.$$

The obtained calculated result is in good agreement with the experimental result on heating water in a given WCH under CHVIA treatment. The measurements were carried out with a M890G tester using a thermocouple. The measured temperature drop from the initial (start) $t_{\text{start}}$ to the final $t_{\text{final}}$ was $\Delta t_{\text{exp}} = t_{\text{final}} - t_{\text{start}} \approx 74 - 20 = 54 \text{ K}$. Hence the conclusion follows that practically all the electromagnetic energy reaching the WCH is released in it in the form of heat. This is of fundamental importance, since both electromagnetic factors (electric and magnetic field strength, voltage and current in the WCH) and thermal energy are synergistically directed (unidirectional) factors. This unidirectional effect leads to an increase in the degree of inactivation of microorganisms in the flowable liquid products processed in the WCH. At the same time, all energy supplied to the WCH is used for its intended purpose - microbiological disinfection of the product processed in the chamber. If we now assume that all the heat released in the chamber is transferred through a heat exchanger to an unprocessed product that has not yet passed through the WCH, then the efficiency $\eta_c$ for the given technological process $\eta_c \approx 85-99.5\%$.

An important indicator is also the specific energy consumption of $E_{sp}$, that is, the amount of energy expended for processing a unit (for example, units of volume or mass) of the product. At CHVIA processing in industrial flowing option, when rational heat exchange is involved, this is the amount of electromagnetic energy $E_{flow}$ introduced into the WCH which in the chamber passes into thermal energy. Here, the product heating $\Delta t_{flow}$ is guaranteed in the flow mode, while it flows through the WCH, by several K (for example, by 5 K) and the transition from the subcritical temperature to the supercritical temperature of the product which ensures irreversible inactivation of microorganisms under the action of high external pulsed electric field.

Estimation of $E_{flow}$ and $E_{sp}$

$$E_{flow} \approx c \cdot V \cdot Y \cdot \Delta t_{flow} = 4200 \text{ J/(kg·K)} \cdot 10^{-4} \text{ m}^3 \cdot 10^3 \text{ kg/m}^3 \times \times 5 \text{ K} = 2100 \text{ J};$$

$$E_{sp} = \frac{E_{flow}}{V} = c \cdot Y \cdot \Delta t_{flow} = 2100 \text{ J} \cdot m^3 = 2.1 \cdot 10^7 \text{ J/m}^3 = = 2.1 \cdot 10^4 \text{ kJ/m}^3 = (2100/3600) \text{ kWh/m}^3 = = 5.83 \text{ kW·h/m}^3.$$

Thus, the estimated value of the specific energy consumption in the flowing mode at CHVIA treatment of products is $E_{sp} = 5.83 \text{ kWh/m}^3$. At the traditional scheme of microbiological milk disinfection (with the help of heat treatment – pasteurization), the specific energy consumption is more, at least 4 times [1, 2].

**Conclusions.**

1. Rational modes of operation of CHVIA installation for the tested working chambers take place at amplitudes of pulsed electric field strength $E \approx 30 \text{ kV/cm}$ in the liquid in the working chamber and at the treatment duration of 20 s with high-voltage pulses of duration 300-1200 ns at pulse repetition rate $n \approx 400$ pulses/s.

2. At rational modes in the treated water, milk whey and milk, the demonstrated *E.coli* bacteria are completely and irreversibly inactivated. In this case, the enzyme peroxidase in milk is preserved. Consequently, the tested rational mode of disinfecting milk treatment is milder than the mode of thermal sterilization, and approximately corresponds to pasteurization.

3. The amount of vitamin C, highly sensitive to various treatments, after treating milk in rational modes is maintained at a level that meets the requirements of regulatory documentation, that is, CHVIA treatment is a soft treatment that preserves the biological and nutritional value of the products.

4. Estimated value of specific energy consumption in flowing mode AT CHVIA treatment of products is $E_{sp} = 6 \text{ kWh/m}^3$, which is about 4 times less than at traditional heat treatment. At the same time, the energy efficiency of the proposed complex of high-voltage pulse actions is 4 times higher compared with pasteurization.

5. The results of the performed investigations open the prospect of the industrial application of a complex of high-voltage pulse actions for the disinfecting treatment of water-containing food products.

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Received 13.03.2018

How to cite this article: