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IDENTIFICATION OF SPECIAL FEATURES IN THE ELECTROLYSIS-CAVITATION WATER TREATMENT IN POOLS

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Розроблена інноваційна технологія електролізно-кавітаційного водоочищення та водопідготовки басейнів. Даний метод належить до групи фізичних методів водоочищення і його перевагою є відсутність потреби у вартісних хімічних дезінфектантах та високий до 97–98 % ступінь очищення води від біологічних та органічних забруднювачів. Типовий технологічний процес електролізного водоочищення, який ґрунтується на електролізному розчепленні кухонної солі із утворенням хімічно активованого гіпохлориду натрію, доповнено операцією кавітаційного знезараження води від органічних та біологічних забруднювачів. Попередня кавітаційна обробка води басейнів на 75–80 % понижує ступінь її забруднення, що приблизно вдвічі понижує потребу в продукованому електролізними апаратами дезінфектанті. Це пропорційно на 45–50 % зменшує тривалість роботи енергозатратного електролізного обладнання і на третину понижує затрати електроенергії на водоочисні операції.

Для кавітаційного знезараження води басейнів розроблено нову конструкцію промислового варіанту віброкавітатора резонансної дії, досліджено умови збурення в ньому кавітаційних процесів, розроблено методику проектування та розрахунків його основних вузлів та деталей. Передуючий електролізному водоочищенню блок віброкавітаторів забезпечує окиснення органічних домішок забрудненої води, у тому числі і сечовиною, до 75–77 %. Ступінь біологічного знезараження води при цьому сягає 80–82 % при продуктивності 3–3,5 м^3/год.

Потужність електромагнітів приводу віброкавітаторів становить 1–1,5 кВт, що на порядок менше порівняно із потужністю електролізних апаратів. Завдяки цьому запропоноване поетапне кавітаційне та електролізне водоочищеня понижує сумарні енергозатрати на здійснення водоочисної операції. Для стандартних басейнів з об'ємом води 3000 м^3 із електролізним водоочищенням запровадження додаткового кавітаційного дозволить щомісячно понизити енергозатрати на водоочисній операції приблизно на 1200–1500 кВт.

Розглянуто правові аспекти використання запропонованих рішень в частині, що стосується виробничого впровадження електролізно-кавітаційного водоочисного процесу та підвищення безпеки користувачів водних процедур та послуг

Ключові слова: кавітаційне очищення води, електролізне очищення води, біологічне забруднення, органічні домішки, хімічно-активні радикали

1. Introduction

The role of water as a human food product and its hygiene products is almost impossible to overestimate. Specifically, water and air in their organic combination with food are the most significant substances for the people and animals existence. Namely, their quality that is decisive for human health. Only spring water, enriched with minerals and useful salts, has healing properties for living organisms. And poor-quality chemically or biologically polluted water is a source of harmful infections and hard to cure diseases (dysentery, cholera, typhoid, etc.). That is why technological processes of water treatment and purification are given increased attention from the standpoint of ensuring proper sanitary and hygienic standards. Among the developers of new water purification methods, we can note work [1], in which the scientists investigated the effect of ultrasonic cavitation treatment on biological contamination of water. The issues of water purification and water preparation are paid due attention by other researchers. Thus, the authors of [2] studied the effect of magnetic fields on the water structure, and in [3], attention was paid to improving the quality of cavitation water purification by bubbling with various gases.

Recently, physical methods, in particular, based on the electrolysis of sodium chloride aqueous solutions, have become increasingly common. At the same time, the OCL ions formed by the electric current as a result of electrolysis splitting of kitchen salt actively disinfect and purify water. However, a significant electrolysis water purification drawback is the high energy intensity of the disinfectant formation process in the form of OCL ions. In this regard, scientists around the world continue to research and search for more advanced physical methods of water purification and water treatment.

From this point of view, the most promising is the combination of electrolysis water purification with other physical methods of water purification, for example, cavitation. This confirms the relevance of research aimed not only at improving the existing physical methods of water purification, but also the development of more advanced new methods.

2. Literature review and problem statement

Among the promising directions for the development of water purification physical methods is the use of cavitation processes for the purification of organic and biological water pollutants. Currently, for the cavitation treatment of liquids and suspensions, most of them use ultrasonic generators and hydrodynamic cavitators. In [4, 5], scientists noted that ultrasonic cavitation treatment is characterized by a high intensity of the formed cavitation field, but it is extremely low-productivity because of the rapid attenuation of the ultrasonic wave in a liquid medium. Energy costs in ultrasonic generators reach 500 W/dm^3, which limits the use of ultrasound to the scope of laboratory research.

Thus, in [6], authors presented results of the ultrasonic cavitation effect studies on water contaminated with organic matter. Shown that, under the influence of a cavitation field, organic additives dissolved in water enter chemical reactions with OH– radicals. As a result of exposure to the organic matter of the cavitation field, organic substances, for example, urea, are converted to CO2 and H2O. In this case, the degree of the source water contamination decreases by 90–95 %. The results of these studies confirm the high efficiency of the cavitation use for water purification. But there were still unresolved issues related to the productivity of polluted water treatment insufficient for water pools purification. The reason for this is that the ultrasonic cavitation effect is efficient only in the zone of the magneto strictive radiator.

An option of overcoming the difficulties caused by the significant volumes of pool water to be purified could be the hydrodynamic cavitation use. This approach was used in [4], where the authors described devices for exciting hydrodynamic cavitation.

At hydrodynamic cavitators, the cavitation field is generated as a result of changes in the speed and geometry of hydraulic flows when they flow around solid bodies or when moving at certain speeds in solid bodies liquids. The most widespread hydrodynamic blade cavitators, which are based on the formation of the cavitation field of a multi-blade impeller rotating in a fluid stream at high speed. The capacity of cavitation treatment of liquids here is quite high and reaches 2÷3 m^3/hour. However, there were unresolved issues related to the low intensity of the cavitation field formed in them. This does not provide high-quality processing of liquids, narrowing the scope of the hydrodynamic cavitators effective use [5, 6].

The authors of [3, 6] note that, regardless of the cavitation field nature excitation, the cavitation effect mechanisms on liquids are mostly identical. The most obvious mechanisms of cavitation in liquids based on water. The authors of [7] note that the stages of nucleation, growth and collapse of cavitation bubbles contribute to the formation of a powerful energy wave, chemical reactions and transformations in the structure of water molecules.

This is confirmed by the results of cavitation processes experimental studies described in [8, 9]. Their authors described the mechanisms of cavitation effects on a variety of organic water pollutants. They note that in the cavitation field in water-based liquids, OH– and hydrogen peroxide radicals are formed, which are highly reactive to chemical oxidative reactions. The lifespan of these single radicals is calculated in milliseconds. But a large number and the continuous formation of new ones, instead of entering chemical reactions, contributes to intensive chemical oxidative reactions with pollutants such as organic. At the same time, the energy of the microwaves produced by the of cavitation bubbles collapse destroys the membranes of the microorganisms, bacteria and yeast that fill the liquid, thereby ensuring disinfection of the treated fluids from biological pollutants. The organics of the destroyed bacteria internal contents and microorganisms under the influence of radicals OH– are converted partially into H_2O and CO_2, and partially deposited in accumulators of the treated liquid [9].

Summing up the results of cavitation effects studies on water, the authors of [9, 11] note that the mechanism of the cavitation effect on the treated fluids is much more multifaceted and more complicated. And it should be noted that a theoretical explanation of it has not been created until today. But the fact that cavitation is able to affect liquids, for example, by reducing the level of their organic and biological contamination [10]. Thus, the scientists been established that cavitation treatment is able to improve the structure of ordinary tap or natural water, modifying it from a cluster structure to a single-crystal structure peculiar to spring water [11].

The use of cavitation for water purification pools prevents the absence of high-performance cavitation equipment. Variants of overcoming these difficulties could be the development described in [2, 4]. But for the most part experimental equipment does not have sufficient performance.

The issues of water purification from biological and organic pollutants by its cavitation treatment have been given attention in a series of works. Thus, the authors of [12], investigated the effect of various modes of water ultrasonic cavitation treatment on its quality indicators, in particular hardness and acidity. They established that cavitation treatment does not affect the water hardness. But on the acidity of water, its effect is very significant – cavitation treatment reduces the high level of acidity by 1–2 units in 4–5 minutes of treatment. Studies on the cavitation treatment intensity effect on biological water pollution are described in [13, 14]. A common conclusion for these works is that, regardless of the biological contaminant varieties, cavitation treatment reduces such an important indicator as their microbial number, which reflects the number of bacteria per unit volume of liquid.

The analysis carried out suggests that it is expedient to conduct a study on the development of a new water purification technology for pools, combining the advantages of electrolysis and cavitation water purification.

3. The aim and objectives of the study

The aim of this research is to develop an improved technology for water purification and water treatment of public water bodies by supplementing electrolysis purification with additional vibrocavitational disinfection of water.

To achieve this goal, the following tasks were set:

– to develop a methodology for calculating and designing low-frequency vibro-cavitators of resonance action for water purification from organic and biological pollutants;

– to determine the main technological and design parameters of vibrocavitators for disinfecting treatment of pool water;

– to develop the technological scheme of the electrolysis-cavitation water purification of pools, to make its experimental approbation for compliance with the provided indicators of the water quality purification of the pool to the requirements of sanitary and hygienic standards.

4. The vibration electromagnetic resonator cavitator design

By comparison with hydrodynamic blade cavitators, low-frequency vibro-cavitators of resonance action consume less energy by 20–25 % [11]. It was achieved by leading to the resonance of cavitation nuclei present in the treated fluid. The cavitation nuclei are microbubbles of air and gases dissolved in a liquid, a variety of particles suspended in a liquid and micro particle.

Experimental studies described at [15, 16] have established that cavitation resonance can be achieved at external force frequencies not only equal to cavitation vibration frequency, but at frequencies that are multiple to resonant. At mechanics, this phenomenon is quite common and is used for technological purposes. For example, in vibration centrifugal machines for hardening machining of parts, in planetary vibration exciters and other similar devices.

The mechanism of this phenomenon is very simple in its essence and is most vividly illustrated by the example of a swing for children – there is no need to push it up in each of the oscillation periods in order to increase the swing oscillation amplitude. It is sufficient with a certain frequency, but the main thing, is to apply a force to the oscillating swing, the direction and vector of which coincide with the direction of oscillation of the swing. At the same time, depending on the frequency and magnitude of the external force, the amplitude of swing oscillations can both decrease and rapidly increase. Experimental confirmation of this phenomenon [15] has become a key stage in the creation of a fundamentally new class of cavitation equipment, called low-frequency vibratory cavitators of resonance action.

A schematic diagram of a ring electromagnetic vibration cavitator with resonance action [10] is shown at Fig. 1. Fig. 2 shows the 3D volume model of this vibrocavitator with a quarter cut for a better perception of its structure. Fig. 3 shows a fragment of a cavitation disturbance deck with an injector nozzle when liquid flows through it, accompanied by the formation of cavitation cavities. Fig. 4 reproduced various (two extreme and average) positions of the oscillating camera.

It consists of chambers: loading 6, working 9 and outtake 14. The working chamber 9 is connected to the loading 6 and outtake 14 with the possibility of relative movements through flexible corrugations 8 and 12. An annular armature 10 fixed from a sheet of iron is enshrined on the working chamber 9. The chamber and armature are connected to reactive masses 11 via brackets 2 and cylindrical elastic rods 5 , which are fixed on the pipes of the loading 6 and the outtake chamber 14. Coaxially the armature 10 to each of the reactive mass 11 fixed on the loading 6 and side chamber 14 of the reactive mass 11 is attached to the body 4 of the electromagnet. At the body of 4, annular stator 15 with coil of winding 3 are located coaxially with armature 10. Each of stators 15 with coil of winding 3 and generic armature 10 (Fig. 1) form two electromagnet 10 symmetrically located with relatively to armature. The electromagnets windings are connected to an alternating voltage network with a phase shift in such a way that in the first half-period of a sinusoidal alternating voltage the armature is gravitating to one of the last electromagnets, and in the second half-period to another electromagnet.

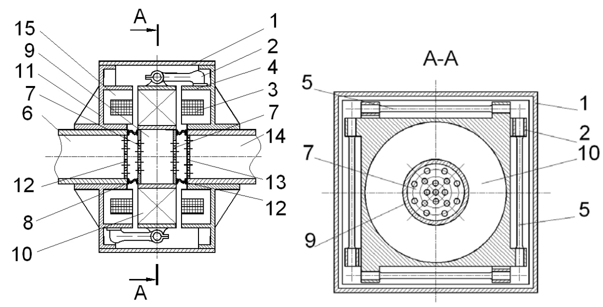


Fig. 1. Schematic diagram of the ring vibration electromagnetic cavitator resonance action: *a* — longitudinal section of the cavitator; *b* — cross-section along the section plane A—A

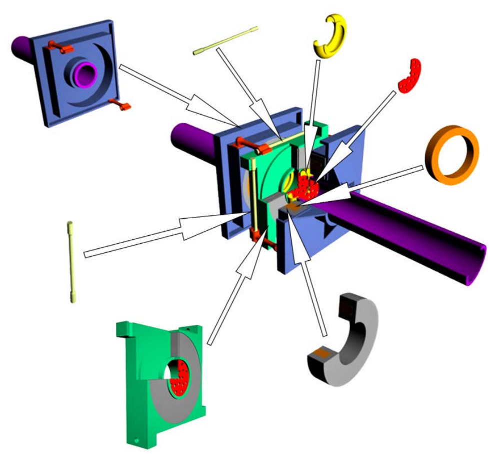
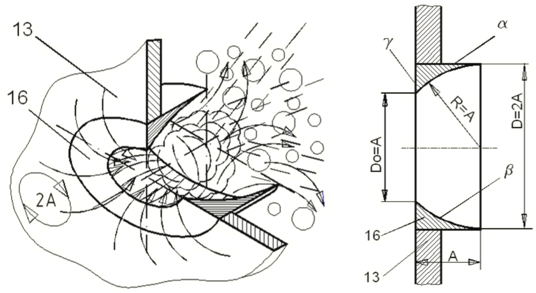


Fig. 2. Volumetric 3D model of vibroresonant electromagnetic cavitator

The coaxially located stators 15 with the coils of windings 3 and armature 10 form with working chamber 9 an annular electromagnetic vibration exciter with two electromagnets and a generic armature. The electromagnetic vibration exciter, in combination with elastic rods 5 attached to the reactive mass, form a two-mass resonant oscillatory system. The first of the oscillating masses is the working chamber 9 filled with the liquid, with armature 10 and decks 7 attached to it, the second — stators 15 with windings 3, reactive masses 11 with massive loading pipes 6 and outtake chambers 14 (Fig. 2).

Decks 7 and 13, cavitation exciters with evenly spaced holes for fluid to flow, are rigidly attached to the armature and stator. The diameters of the holes in decks 7 and 13 are equal to the amplitude of oscillations of the working chamber, and the distance between adjacent holes is three times the amplitude. A pair of decks attached to the armature and stator are placed symmetrically at the entrance and outlet of the working chamber 9.

From hitting third-party objects to oscillating systems, the electromagnetic vibration exciter is protected by casing 1.



a *b*

Fig. 3. Fragment of a cavitation disturbance deck with an injector nozzle when fluid flows through it forming cavitation cavities (numbering of positions, accordingly, in Fig. 1): *a* – a formation model of a cavitation field; *b* – nozzle section for water flow

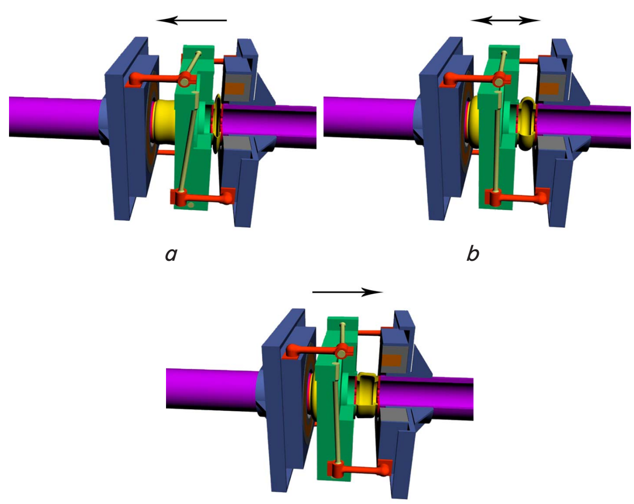
To intensify the disturbance of cavitation cavities when flowing through decks 7 and 13 of the treated liquid to the deck holes, nozzles 16 are pressed with cylindrical outer α and spherical β inner surfaces (Fig. 3). Diameter of the cylindrical surface D=2A and the radius of spherical inner surface *R*=2A equal to the scope, that is, the double value of the amplitude A of the oscillations of the deck. In the intersection with the end plane of the injector-nozzle 16, the inner spherical surface forms a γ hole for the flow of fluid, the diameter of which is equal D_0=A. This hole nozzle 16 faces in the direction opposite to the direction of the treated fluid flow (Fig. 3).

5. Describing the electromagnetic vibrocavitator

The work of the vibration electromagnetic cavitator is as follows. Using a loading chamber 6 pipe, working chamber 9, under a slight pressure or by gravity, is fed the treated fluid. At the same time, a voltage is applied to the windings of the coils of the electromagnets and offset in phase. The electromagnets alternately attract the armature 10 with the working chamber 9 filled with the liquid, while bending the elastic cylindrical rods 5. The deflection and elasticity of the cylindrical rods 5 are designed in the way when they provide resonant oscillating modes of the working chamber 9 and make it impossible for the armature 10 to strike the stators 15 between each other (Fig. 1). The alternating attraction of the armature 10 to the electromagnets 15 is transformed into directional plane-parallel oscillatory movements of the working chamber filled with the liquid being processed. These oscillations occur with certain calculated amplitudes and a frequency equal to twice the frequency of applying voltage to the electromagnetic vibration exciters ring coils. So, with the frequency of the windings 3 supply network alternating voltage of electromagnets 50 Hz, the oscillation frequency of the working chamber 9 will be equal to 100 Hz. Together with the oscillating working chamber 9, plane-parallel movements are carried out and attached to the chamber of the deck 7 with holes, intersecting the processed liquid flow continuously flowing into this chamber. As the oscillating decks 7 approach the fixed decks 14, the fluid pressure between the decks increases, which helps push the treated fluid through the holes in the fixed decks 14 at a speed equal to the speed of the decks 7.

With recommended oscillation amplitude of 1.5–2 mm and a frequency of 100 Hz, the speed at which the deck crosses the fluid flow is 0.95–1.15 m/s. The coaxial arrangement of oscillating and fixed decks when they approach each other increases the pressure and speed of the hydraulic flows through the holes. As a result, liquid jets lose density. At the same time, from cavitation nuclei always present in the liquid, avalanche is generated, increases in its volume and collapses the cavitation bubbles, which form a high-intensity cavitation field. The uniform arrangement of the holes in decks 7 and 14 ensures the cavitation field uniformity intensity over the entire cross-sectional area of the working chamber 9, that is, the uniform processing of the liquid.

This speed of the liquid jet is sufficient for the formation of air cavitation cavities from the cavitation present air and gases in the liquid being processed from the air and gases dissolved in it. When moving the air cavities along the spherical inner surface of the injector-nozzles 16, the pressure inside the cavities rapidly increases, increasing their volume, as a result of which the cavity leaves impulses of shock waves in the processed liquid at the exit of the nozzle (Fig. 3). The uniform arrangement of the holes in the decks ensures the cavitation field uniformity intensity over the entire cross-sectional area of the working chamber, that is, the uniform processing of the liquid.



a *b* *c*

Fig. 4. Different positions of an oscillating vibrocavitator chamber: *a* – left, *b* – middle, *c* – right

Owing to the symmetrical arrangement of the cavitation deck-exciters fluid flowing through the working chamber 9 is twice amenable to cavitation treatment. After passing the working chamber of a double cavitation treatment, the liquid through the discharge chamber 14 is discharged for subsequent target use.

The fluids quality control processed in the vibratory electromagnetic cavitator of the resonance action is carried out by adjusting the intensity of the cavitation field formed by them in liquids. The intensity depends on A amplitude of the cavitation de-cavitator oscillations, the frequency of these oscillations and the diameter of the holes D0 for the flow of fluid. The amplitude of decks oscillations is regulated by changing the magnitude of the current supplying the electromagnets coils. With a change in the current strength magnitude, the force of stator armature gravity to the electromagnets changes. The magnitude of the current determines the spatial displacement, that is, the range and amplitude of the cavitation de-cavitator oscillatory displacement. The decks oscillation frequency is regulated by means of a thyristor circuit for regulating the frequency of applying voltage to the windings of the electromagnet supply coils. With a change in the voltage frequency, the armature attraction frequency to the electromagnets of the stator changes, that is, the frequency of decks spatial displacement that are rigidly connected with the armature to cavitating. The optimal values of the oscillations amplitude and frequency are selected empirically depending on the physical parameters of the processed fluids – their density, viscosity, surface tension forces. Special attention in the selection of cavitation technological parameters processing is given to the choice of oscillation frequencies of decks. The frequency of vibrations is sought to pick up as close as possible in multiplicity to the natural frequencies of dissolved gases oscillations and air present in the particular liquid being treated, which play the role of cavitation germs. This ensures the implementation of cavitation processing in the so-called resonant mode with minimal energy loss.

To improve the liquids cavitation treatment efficiency in a vibroresonant cavitator, a system for supplying gas to the working chamber 9 is provided (not shown in the Figures). When disinfecting pool water, it is advisable to use oxygen or nitrogen as a concomitant gas treatment [15, 16]. The flow rate of the gas is chosen depending on the degree of water pollution from the range (15÷25) dm^3 per cubic meter of treated water. The gas flow into the working vibrocavitator chamber is due to the need to compensate for the phenomenon of degassing the treated fluid, which always accompanies the cavitation processes [17].

6. The method of calculating the vibration electromagnetic resonator cavitator action

The calculation of the oscillating systems elasticity, the power of the drive electromagnets and their structural elements was carried out using generally accepted methods for calculating vibratory machines with an electromagnetic actuator [18].

Devices for vibroresonant cavitation treatment of liquids provide two groups of variable control parameters provided by it for the quality indicators of cavitation processing, namely, the group of design and the group of technological parameters.

The structural group here includes:

– frequency of deck-cavitator disturbers oscillations, which is regulated by a frequency controller installed in the control panel, for example, model AFC-120;

– the oscillation amplitude of cavitation deck-disturbers, which is regulated by the power and design parameters (the gap between the armature and stator) of the drive electromagnets and the elastic system rigidity (rods 5) of the decks suspension;

– the direction of cavitation-induced disturbers oscillations (along or across the treated liquid stream), which is caused by the location of the drive electromagnets.

The main task of changing the design parameters here is to change the speed and directions of the spatial movements of cavitation deck-disturbers in a liquid stream. This affects the range of vibroresonant excitation of cavitation.

The technological group here includes:

– pressure and velocity of the treated fluid at the site of cavitation treatment. They are regulated by the flow rates (pump and choke of the supply pipeline) of supplying the treated liquid to the working section;

– the type, quantity and pressure of the associated gas treatment or air. They are regulated by throttling the gas supply pipe;

– the number of cavitation nuclei in the treated liquid, which is regulated by the amount of gas supplied to the treatment site.

The main task of changing technological parameters is the influence on the energy state of the treated fluid, the effect on the duration of its processing.

Consequently, changes in the design and technological parameters effectively influence the strength of the treated fluid, its ability to be disturbed and the stable existence of cavitation phenomena in it. Thus, they affect the intensity of the cavitation field formed in the liquid. This determines the liquids cavitation treatment quality.

A feature of vibrational cavitators, as well as any other type of cavitators, is the need to provide a certain energy impact on the processed fluid. This level of energy impact, which is accompanied by a disturbance in the fluid of cavitation phenomena, initiating the effective flow of specific physical processes and chemical reactions in the treated medium. From the positions of molecular physics, the creation of certain prerequisites for the appearance and subsequent growth of cavitation-field cavitation nuclei in a liquid is governed by the dimensionless Reynolds complex Re. The Reynolds number Re number Re relates changes in the characteristics of the certain density and viscosity of liquids flow with a change in the velocity and pressure of the fluid. Critical Reynolds Number Re_{cr} can be interpreted as a parameter that determines the threshold of nucleation in the liquid substance cavitation. In mathematical expression, the Reynolds number *Re* is [4, 5]

$$\mathrm{Re}=\frac{\rho\cdot\upsilon\cdot L}{\mu}=\frac{\upsilon\cdot L}{\nu}, \tag{1}$$

where ρ is the medium density, kg/m^3; υ is the fluid flow rate, m/s; μ is the viscosity dynamic coefficient, Pa/s; here $\nu=\frac{\mu}{\rho}$ is the kinematic viscosity, m^2/s; L is the equipment specific linear dimension, m.

The Reynolds *Re* in a certain way displays the relationship between the nature of the liquid flow and its speed.

For liquid substances with a density and viscosity close to the density and viscosity of water, the critical Reynolds number Re_{cr}, as a rule, slightly exceeds the value $(1{,}5...2{,}0)\cdot 10^5$, that is, $\mathrm{Re}\geq(1{,}5...2{,}0)\cdot 10^5$ [4].

Therefore, asking in equation (1) the numerical values of the treated fluid parameters and the critical Reynolds number Re_{cr}, it is possible to determine the critical speed of vibrocavitator actuators oscillatory movements, that is, their oscillating decks, from the dependence V_D^*

$$V_D^* = \frac{\mu \cdot \mathrm{Re}_{cr}}{\rho \cdot L_D} = \frac{\upsilon \cdot \mathrm{Re}_{cr}}{L_D},$$

where L_D is the total reduced length of the oscillating deck holes circumference, m.

In the case of several decks simultaneous use at a working position, which oscillate in antiphase, the speed of each oscillatory movements V_D can be reduced by the total number of these deck n, that is

$$V_D = \frac{V_D^*}{n}.$$

The average speed of any vibrating bodies oscillatory motions, including deck-cavitation disturbers, the so-called vibration velocity, is limited by the frequency f and A amplitude of their oscillations. Therefore, given, for example, the amplitude A oscillations and equating speeds between themselves $V_k = V_D^*$, determine the required oscillation frequency deck, that is

$$f = \frac{V_k}{2 \cdot \pi \cdot A} = \frac{\mu \cdot \mathrm{Re}_{cr}}{2 \cdot \pi \cdot A \cdot \rho \cdot L_D} = \frac{V \cdot \mathrm{Re}_{cr}}{2 \cdot \pi \cdot A \cdot L_D}.$$

Drive force F_T proportional to the total pressure $\sum P_c$ on the oscillating deck, the total area $\sum S_0$ the surface of the holes for the fluid flow in the oscillating deck and corner β inclination of oscillating decks to the flow direction of the treated liquid, that is

$$F_T = (\Sigma P_c) \cdot (\Sigma S_0) \cdot \sin\beta.$$

Owing to propelling power F_T oscillating deck when it moves overcomes resistance from the treated fluid.

In the case of traditional single and dual mass resonant vibration structures, the pull force of electromagnetic vibration exciters is calculated from formula [3]

$$F_T = \frac{M_0 \cdot \omega^2 \cdot A}{\lambda \cdot Z^2},$$

where M_o is the so-called reduced oscillating mass, which in this case is the total oscillating mass of the working chamber. It includes m_1 armature mass vibrodrive electromagnet, reduced mass of an elastic oscillatory system m_2 treated fluid m_3 with density ρ in the working chamber V, mass m_4 oscillating deck with holes for the fluid flow in the amount of fastening elements to it sealing the corrugation, that is

$$M_o = m_1 + m_2 + m_3 + m_4 = m_1 + m_2 + \rho \cdot \upsilon + m_4.$$

$\omega = 2 \cdot \pi \cdot f$ is the cavitation Disturbance Circular Frequency; f is the oscillation frequency of the armature electromagnet; A is the relative oscillation amplitude of the oscillating system.

Here

$$\lambda = \frac{1}{\sqrt{(1 - z^2)^2 + 4 \cdot \gamma^2 \cdot z^2}}$$

is the dynamic coefficient, in which the resistance index value γ for a steel elastic system without structural hysteresis γ=0.004...0.006; for rubber elastic systems γ=0.1...0.15; z is the resonance tuning factor.

The parameter for resonant modes of vibration equipment operation, as the size of the oscillating working chamber elastic suspension rods, is determined from the following considerations. The length of the cylindrical rod of the elastic suspension is set structurally to the maximum allowable length, and the diameter of the rod d is determined from dependence [18]

$$d = 2\sqrt[4]{\frac{C \cdot l^3}{3E \cdot \pi \cdot n \cdot k}},$$

where E is the rod material elasticity modulus; C is the working chamber rod elastic suspension stiffness, which is determined from dependence

$$C = M_0 \left(\frac{\omega}{Z}\right)^2,$$

n is the number of elastic suspension rods; l is the elastic suspension rod length; k=0.80–0.85 is the inching coefficient of elastic suspension rods

7. The basic technological scheme of water pool purification using vibro-cavitators

Electrolysis water purification in Ukraine at private enterprise is the common thing. Electrolysis machines are simple and reliable in operation, sufficiently productive to ensure high-quality water purification of medium-sized pools with a capacity about 3,000 m^3 of water. Electrolysis water purification in Ukraine in private enterprise is the common thing. Electrolysis machines are simple and reliable in operation, sufficiently productive to ensure high-quality water purification of medium-sized pools with a capacity about 3,000 m^3 of water. When using them, there is no need for expensive chemical disinfectants. However, the disadvantage of electrolysis machines is their high energy consumption. For example, the “Sivash” USR-1000 electrolytic installation common in Ukraine, produced in Russia, consumes about 10 kW of electricity per hour. With its 10-hour operation per day, a double water treatment is provided for an average-sized pool with a capacity of 3.0–3.5 thousand cubic meters of water [19]. The daily consumption of electricity for water treatment is about 100 kW. Such high energy consumption negatively affects the cost of services for water procedures consumers.

The program and methods of experimental approbation are described in detail at [15, 19]. The main parameters monitored were:

– the degree of water pollution by biological pollutants;
– water hardness;
– water acidity;
– the degree of water purification from organic and biological pollutants;
– daily consumption of electricity by the purification equipment for a yard water pool treatment with a capacity of 3.0 thousand cubic meters of water.

The above-mentioned indicators were measured before and after water purification using standard methods for measuring sanitary and hygienic indicators of water [15, 19]. The daily energy consumption of the cleaning equipment was measured with standard power consumption meters [18].

Comparative studies were conducted for two water treatment technologies – traditional electrolysis water treatment and the proposed technology of electrolysis and cavitation water purification.

The program of comparative tests provided for 10 hours of the "Sivash" electrolysis apparatus USR-1000 work per day with traditional electrolysis water purification. At the compared technology of electrolysis-cavitation water purification, the total 10-hour equipment operation time was distributed equally for 5 hours for the alternate operation of the electrolysis apparatus and a block of two vibro-cavitators with a capacity of 1.5 kW/hour each.

We established that with the same initial values of water pool pollution level with organic substances, which is 5–6 % and the degree of biological pollution, respectively, 1.5–2.5 %, the degrees of water purification for both compared technologies are approximately the same. For typical electrolysis water treatment technology, the degree of water purification from organic pollution is 97–97.5 %, and 96–96.5 % of biological pollutants. For the proposed technology of electrolysis-cavitation water purification, respectively, 96–96.5 % and 98–98.5 %. In both compared technologies, these important indicators significantly exceed the permissible sanitary and hygienic standards.

Neither of the compared technologies has a significant impact on the water hardness, both water treatment technologies reduce the acidity of water by 1.0–1.5 units, bringing it closer to neutral. Practically both water treatment technologies are comparable in terms of the main indicators of water purification quality.

A significant difference is observed only in terms of electricity consumption. The cleaning equipment of a standard electrolysis water treatment per day consumes about 100 kW of electricity, the proposed electrolysis cavitation treatment – 65–70 kW. For a month of operation with 25 working days, this difference in the consumed electricity will average 850 kW, for the year – about 10 thousand kilowatts.

A two-fold decrease, from 10 to 5 hours per day, in the electrolysis machines operating time in the proposed technological process of electrolysis and cavitation water purification, and accordingly the reduction of energy consumption for their operation, has a simple explanation. In fact, after the preceding electrolytic cavitation water treatment, the pool water has already been purified to 75–77 % of organic matter and up to 80–82 % of biological pollutants. Accordingly, a smaller amount of disinfectant is required for its final post-treatment, and, accordingly, the operating time of electrolysis machines is less. During the idle time of electrolysis devices, vibro-cavitators work for 5 hours. But their total electricity consumption is only 3 kW/hour versus 10 kW/hour consumed by a single electrolysis apparatus.

The flow chart of the electrolysis cavitation purification and disinfection of the water pools and closed public water bodies is shown at Fig. 5. This water treatment scheme provides a closed-loop circulation loop that includes a water filtration unit with coarse and thin filters, electrolytic water purification devices of the "Sivash" type USR-1000, a cavitation water purification unit with several electromagnetic vibration resonators and a gas supply system into working chambers of vibrocavitators.

Depending on the volume of pool water to be cleaned daily, the cavitation purification unit includes 2...4 vibroresonant cavitators. The capacity of each cavitator is 3...3.5 m^3/h with a power consumption of 1...1.5 kW/h. Nitrogen was used as a concomitant cavitation treatment of gas water with the flow rate of its supply to the cavitator working chamber equal to 0.15 dm^3 for each cubic meter of water being treated.

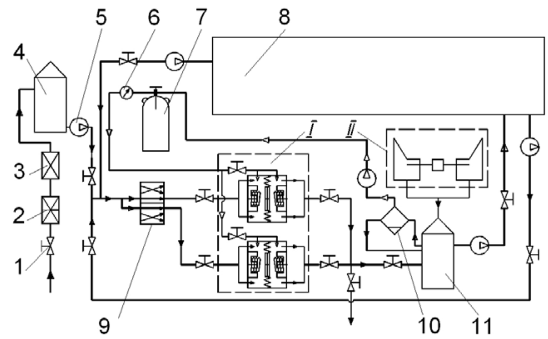


Fig. 5. Technological scheme of public water bodies electrolysis and cavitation water purification: 1 – adjusting valve, 2 – coarse filter, 3 – fine filter, 4 – storage tank, 5 – pump, 6 – pressure gauge, 7 – gas cylinder, 8 – pool, 9 – pneumatic switch of water flow, 10 – separator, 11 – accumulative capacity of mixing water with disinfectant, I – block of vibrocavitators, II – block of electrolysis preparation of disinfectant

The total water treatment system includes three independent circuits. The first circuit is designed for water treatment coming directly from the city water mains or reserve water tanks to fill the pool. Here, having passed the filtration unit, water is supplied to the working chambers of vibrocavitators, where it is purified from organic and biological pollutants. After vibrocavitators, the purified water enters the storage tank, where it mixes with the sodium hypochlorite formed in the electrolysis unit and disinfected. After settling, the final prepared water is served to fill the pool.

The second circulation circuit is designed for cyclic disinfecting treatment of polluted pool water. Here, polluted water entering through the pool overflow system enters the vibro-cavitation cleaning position, then is mixed in the storage tank with disinfectant and water filling the storage tank and pumps is re-fed into the pool. This circulation water purification is carried out periodically, approximately 3–4 times a day, depending on the degree of water pollution and the mode of pool operation.

The third circuit of the proposed water treatment system is designed to clean the contaminated pool water before it is discharged into the sewer system. In this circuit, the water after filtration and disinfection in vibrocavitators is discharged into the storm or sewer urban system.

8. Discussion of electro-cavitation water purification research results

Studies of the electrolysis-cavitation water purification process have testified to its ability to provide adequate indicators of the water purification quality combined with tangible cost-effectiveness. Ecological efficiency is manifested in the reduction by a third of the energy and gas consumption for the implementation of the water treatment process in comparison with the traditional electrolysis water treatment. Therefore, this development has not only the potential and ability to patenting the proposed technical solution, but also the ability to comply with its practical implementation.

The perspective of the production implementation of the electrolytic cavitation water treatment process is advisable to implement with the involvement of investor funds. Investors involvement in the process of introducing the process is inextricably linked with the legal coordination of the concerned parties' interests. In a certain way, this is due to the fact that an integral component of the new water treatment process, namely the cavitation treatment, is implemented on a new patent protected by Ukraine for the invention of cavitation equipment. Consequently, the introduction of the electrolysis-cavitation water treatment process have to be preceded by legal coordination of various legal and physical parties interests. In particular, the owners of patents in Ukraine on the design of vibrocavitators, manufacturers of new cavitation equipment, as well as firms and enterprises operating it. In this situation, we cannot do without legal agreements between the concerned parties, without proper legal support of the whole works complex on the implementation of the innovative water treatment process.

It is preferably not to discard quite possible force majeure. For example, it is advisable from a legal point of view to foresee and stipulate the responsibility of stakeholders in the case when the practical implementation of a new water treatment equipment and relevant technical solutions does not provide the expected results at the start-up and production tests stage. In this situation, there may be valid claims from investors of this project. It is quite possible and precedents in the context of violations of the water procedures consumers rights due to insufficient quality water purification during the test period. We cannot exclude the probability of damage to the pool users through failures in the operation of new equipment during its testing phase. All this must necessarily be specified in the relevant legal agreements and legal documents.

The combination of two complementary physical methods of water purification, namely, cavitation and electrolysis treatment of pool water, allowed for a 30–35 % reduction in energy costs for water treatment. It can be explained by the fact that previous electrolysis cavitation purification of water by 75–77 % reduces the degree of its contamination with organic inclusions. At the same time, the level of water pollution by bacteria decreases by 80–82 %. As a result, the position of electrolysis purification receives more purified water with reduced levels of organic pollution to 1.25–1.38 % and reduced biological indicators to 0.3–0.45 %. Accordingly, a smaller amount of disinfectant produced by electrolysis devices is required for its final purification. This reduces the time of their work and the electricity they consume.

Comparing with existing water treatment technologies, for example, the widespread water purification of pools with hydrogen peroxide H_2O_2 [19], the proposed technology of electrolysis-cavitation water purification increases the degree of water purification from biological pollution by 15–18 %. This is due to the active destructive effect of micro-impact waves generated during the collapse of cavitation microbubbles on the bacteria shells and walls that pollute water [17].

The issues of proper high-quality water treatment and purification of pools are inextricably linked not only with the ecology of the environment, but also with the health, and at times, and safety of water procedures users. Thus, in the territory of Ukraine in recent years there have been several fatal accidents that are directly related to the water quality of the pools.

In particular, this is the death of a child who has choked with water in the pool of Kyiv, and on November 28, 2017, in the water, the 25-meter pool of the I. Franko National University student (Lviv). And if the death of a child can still be explained by the carelessness of the parents who took care of him, then the main reason for the death of an adult young man is excessively polluted water. According to the press service of the General Directorate of the National Police in the Lviv region, citing data from the investigative commission, there were about a dozen other swimmers with the deceased student in the pool, there were a trainer-teacher with other students on the pool side. But due to excessively polluted water that lost its transparency, the body of the deceased at the bottom of the pool was not noticed in time. Upon the death of a student, a criminal case was initiated under Part 2 of Article 367 of the Criminal Code of Ukraine "official negligence, entailing grave consequences".

Of course, from a legal point of view, there is an unfair implementation by the teacher and employees of the pool. But it is impossible not to take into account the circumstance that mitigates their guilt – the excessively polluted water of the pool that has lost its transparency hides the body of the student lying at the bottom. For the purification of water at the time of the accident, we used an obsolete reagent chlorination method. Getting into the polluted water solutions of chlorine and other chemical disinfectants, of course, clean it from organic and biological pollutants. But at the same time, the water loses its transparency, and muddy sediments settle at the pools bottom and the walls, preventing observation of swimmers. Physical non-reagent methods of water treatment, as opposed to chemical, do not reduce, but increase the transparency of water. This once again confirms the advantage of the physical methods of water purification, to which the described electrolysis-cavitation water purification belongs.

It is well known that the aquatic environment is a medium of increased danger. Therefore, from a legal point of view, bearing in mind possible threats to the health and life of water procedures users, it is necessary to secure them at the legislative level. In this regard, it is obviously meaningful to supplement the list of sanitary and hygienic indicators standards and requirements for the quality of water in the pools with the requirement to ensure the necessary degree of water transparency. Even more effective would be the legislative norm of obligatory equipping each user of water procedures with personal protective equipment. For example, the requirement to supply each swimmer and bather, regardless of gender, age and skills of handling the aquatic environment with special signaling electronic devices. It could be used, for example, individual waterproof wrist straps-sensors pulse rate of a person. Such sensors can be supplemented with hazard warning devices. For example, excessively high heart rate or lack of pulse for a certain time. Technically, to do this, considering the current level of electronics development, it is doable.

Along with the cavitators use of the proposed design for water pools purification in the future, they can also be used for water treatment in agriculture. The results of experimental studies confirming the efficiency of using cavitation-treated water for irrigation of crops, are given in [19]. Given the relatively high, in comparison with ultrasonic cavitation devices [20, 21], performance of proposed design vibrocavitators, they can be recommended for various purposes. For example, for the treatment of natural water reservoirs, which is used for growing fish, drinking and preparing feed in animal husbandry, while irrigating agricultural plants. This is explained by the fact that cavitation treatment of water not only purifies it from biological and organic pollutants, but also improves the structure, transforming it from a cluster structure into a monomolecular state, spring water [19] characteristic. And it is well known that in the monomolecular state, water is better absorbed not only by plants, but also by living organisms, having a beneficial effect on the digestive organs and the circulatory system.

Nevertheless, this study has certain limitations regarding the degree of the initial water entering contamination. The studies were carried out with the use of water contaminated with organic substances, including urea, by 5–6 % mass percent. This is the degree of water pollution characteristic of most pools. There are certain disadvantages in this, since it is not known how effective electro-cavitation cleaning will be at higher levels of contamination. It is possible that in this case additional water purification will be needed before it is fed to the cavitation treatment position, for example, chlorination. It is also impossible to exclude the option of possible reusable electro-cavitation water purification in an internal closed loop prior to its supply to the pool. However, in this case, arrangement of additional water storage tanks will be required, which entails additional costs. Given this, it is possible to predict the direction of further development of this research in the cavitation devices improvement field for water purification. This can be accomplished, for example, by a combination of contaminated water simultaneous treatment by cavitation and electromagnetic fields. But, of course, this implies the need for a series of experimental and theoretical studies.

9. Conclusions

1. The conditions for the excitation of cavitation processes by low-frequency vibrations are determined and theoretically justified, the dependences for calculating the speeds of cavitation exciters spatial movements in a liquid flow, their vibration frequencies, and the main parameters of vibroresonant cavitators drive. With the oscillations frequency of cavitation disturbers 100 Hz, the speed of their movement in the treated water is in the range of 0.95–1.15 m/s, which ensures the formation of a high-intensity cavitation field.

2. We experimentally determined the main technological and design parameters of vibroresonant cavitators for cleaning pool water, which have a prevailing effect on the performance and quality of its disinfecting treatment. The frequency and amplitude of cavitation disturbers oscillations and the gases accompanying cavitation treatment of water exert the most significant influence on the quality of water treatment in pools.

3. Experimental testing of the proposed technological scheme of electrolysis-cavitation purification of the pool water, providing for a phased preliminary cavitation treatment with subsequent electrolysis purification of water, showed its viability to meet the requirements of sanitary and hygienic standards for pool water. The degree of the pool water purification from organic matter provided by this is within 96–96.5 %, and from biological pollution – within 98–98.5 %.

References

1. The Effect of Ultrasonic Irradiation on the Anaerobic Digestion of Activated Sludge / Farooq R., Rehman F. et. al. // World Applied Sciences Journal. 2009. Vol. 6, Issue 2. P. 234–237.
2. Silin R. I., Hordieiev A. I. Tekhnolohiya hidrokavitatsiynoi obrobky vody ta metodyka rozrakhunku elementiv pryvodu obladnannia // Avtomatyzatsiya vyrobnychykh protsesiv u mashynobuduvanni ta pryladobuduvanni. 2006. Issue 40. P. 221–228.
3. Koval I. Z., Starchevskyi V. L. Intensyfikuiucha diya barbotovanykh haziv u protsesakh ultrazvukovoho znezarazhennia vody // Naukovi visti Natsionalnoho tekhnichnoho universytetu Ukrainy "Kyivskyi politekhnichnyi instytut". 2012. Issue 1. P. 137–140.
4. Viten'ko T. N., Gumnitskii Y. M. A mechanism of the activating effect of hydrodynamic cavitation on water // Journal of Water Chemistry and Technology. 2007. Vol. 29, Issue 5. P. 231–237. doi: https://doi.org/10.3103/s1063455x07050037
5. Shevchuk L., Aftanaziv I., Falyk T. Vibrocavitation decontamination of brewing yeast-containing wastewater // Chemistry & Chemical Technology. 2017. Vol. 11, Issue 4. P. 475–479. doi: https://doi.org/10.23939/chcht11.04.475
6. Kinetic regularities of the processes of accumulation and destruction of microorganisms in water at bubbling of the different gases / Koval I., Kislenko V., Shevchuk L., Starchevskyy V. // Chemistry & Chemical Technology. 2011. Vol. 5, Issue 4. P. 463–467.
7. Koval I., Shevchuk L., Starchevskyy V. Ultrasonic Intensification of the Natural Water and Sewage Disinfection // Chemical Engineering Transaction. 2011. Vol. 24. P. 1315–1320. doi: http://doi.org/10.3303/CET1124220
8. The effect of carbon dioxide on the viability of bacteria of Bacillus and Diplococcus genera / Koval I. Z., Kislenko V. N., Starchevskii V. L., Shevchuk L. I. // Journal of Water Chemistry and Technology. 2012. Vol. 34, Issue 2. P. 112–116. doi: https://doi.org/10.3103/s1063455x12020075
9. Whey Disinfection and its Properties Changed under Ultrasonic Treatment / Kondratovych O., Koval I., Kyslenko V., Shevchuk L., Predzumirska L. // Chemistry & Chemical Technology. 2013. Vol. 7, Issue 2. P. 185–190. doi: https://doi.org/10.23939/chcht07.02.185
10. Vibratsiynyi elektromahnitnyi kavitator: Pat. No. 107769 UA / Aftanaziv I. S., Strohan O. I., Shevchuk L. I., Starchevskyi V. L. No. a201400823; declareted: 29.01.2014; published: 10.07.2014, Bul. No. 13.
11. Shevchuk L. I., Aftanaziv I. S., Strohan O. I. Vibratsiynyi elektromahnitnyi kavitator rezonansnoi diyi // Avtomatyzatsiya vyrobnychykh protsesiv u mashynobuduvanni ta pryladobuduvanni. 2011. Issue 45. P. 374–379.

12. Effect of ultrasonic frequency on separation of water from heavy crude oil emulsion using ultrasonic baths / Antes F. G., Diehl L. O., Pereira J. S. F., Guimarães R. C. L., Guarnieri R. A., Ferreira B. M. S., Flores E. M. M. // Ultrasonics Sonochemistry. 2017. Vol. 35. P. 541–546. doi: https://doi.org/10.1016/j.ultsonch.2016.03.031
13. Assessment of ultrasound irradiation on inactivation of gram negative and positive bacteria isolated from hospital in aqueous solution / Maleki A., Shahmoradi B., Daraei H., Kalantar E. // Journal of Advances in Environmental Health Research. 2013. Vol. 1, Issue 1. P. 9–14.
14. Adhikari U., Goliaei A., Berkowitz M. L. Mechanism of Membrane Poration by Shock Wave Induced Nanobubble Collapse: A Molecular Dynamics Study // The Journal of Physical Chemistry B. 2015. Vol. 119, Issue 20. P. 6225–6234. doi: https://doi.org/10.1021/acs.jpcb.5b02218
15. Research into effectiveness of cavitation cleaning of wastewater of a fatandoil plant from organic and biological contamination in the presence of various gases / Vashkurak U., Shevchuk L., Nykulyshyn I., Aftanaziv I. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 3, Issue 10 (93). P. 51–58. doi: https://doi.org/10.15587/1729-4061.2018.131953
16. Whey Disinfection and its Properties Changed under Ultrasonic Treatment / Kondratovych O., Koval I., Kyslenko V., Shevchuk L., Predzumirska L. // Chemistry & Chemical Technology. 2013. Vol. 7, Issue 2. P. 185–190. doi: https://doi.org/10.23939/chcht07.02.185
17. Biopolymers for Seed Presowing Treatment / Struminska O., Kurta S., Shevchuk L., Ivanyshyn S. // Chemistry & Chemical Technology. 2014. Vol. 8, Issue 1. P. 81–88. doi: https://doi.org/10.23939/chcht08.01.081
18. Lanets O. S. Vysokoefektyvni mizhrezonansni vibratsiyni mashyny z elektromahnitnym pryvodom (Teoretychni osnovy ta praktyka stvorennia): monohrafiya. Lviv: Vyd-vo Nats. Un-tu «Lvivska politekhnika», 2008. 324 p.
19. The growth of agricultural plants with the modern water treatment technologies / Aftanaziv I. S., Shevchuk L. I., Strogan O. I., Falyk T. S. // Scientific Bulletin of UNFU. 2018. Vol. 28, Issue 6. P. 23–29. doi: https://doi.org/10.15421/40280604
20. Feasibility of low frequency ultrasound for water removal from crude oil emulsions / Antes F. G., Diehl L. O., Pereira J. S. F., Guimarães R. C. L., Guarnieri R. A., Ferreira B. M. S. et. al. // Ultrasonics Sonochemistry. 2015. Vol. 25. P. 70–75. doi: https://doi.org/10.1016/j.ultsonch.2015.01.003
21. Effect of ultrasonic frequency on separation of water from heavy crude oil emulsion using ultrasonic baths / Antes F. G., Diehl L. O., Pereira J. S. F., Guimarães R. C. L., Guarnieri R. A., Ferreira B. M. S., Flores E. M. M. // Ultrasonics Sonochemistry. 2017. Vol. 35. P. 541–546. doi: https://doi.org/10.1016/j.ultsonch.2016.03.031