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Electromagnetic vibratory cavitator

***Abstract**. It was found that the principles and regularities of the multiplicity frequency apply to hydraulic objects, and in particular to suspended in liquid medium its foreign objects - air and gas bubbles, solid particles, and similar formations. Vibrational resonant cavitators provide 25÷30% increase of the intensity of cavitation field, hence, proportional productivity increase of cavitation liquid treatment, comparing with hydrodynamic cavitators.*

***Streszczenie.** Wykryto, że zasady i reguły częstotliwości powielonych mają zastosowanie do obiektów hydraulicznych, a w szczególności do ciał obcych zawieszonych w ośrodku ciekłym, takich jak pęcherzyki powietrza i gazu, cząstki stałe, itp. Wibracyjne kawitatory rezonansowe zapewniają wzrost intensywności pola kawitacji o 25÷30%, a więc także proporcjonalny wzrost wydajności płynu kawitacyjnego, w porównaniu z kawitatorami hydrodynamicznymi. (**Elektromagnetyczny kawitator wibracyjny**).*

Keywords: liquid treatment, cavitation, vibratory cavitator, electromagnetic vibratory cavitator.
Słowa kluczowe: kawitacja, kawitator wibracyjny, elektromagnetyczny kawitator wibracyjny.

Introduction

In recent decades the technological processes using cavitation treatment of the liquids are finding increasing use. This is due to the specific beneficial physical and chemical effects of cavitation in the processed liquid, which they take as a result of cavitation processing of unique properties. So established that cavitation treatment able to improve the structure of ordinary tap water or natural water, modifying it from the cluster structure to monocrystalline, peculiar structure of spring water. Using cavitation greatly increases the yield of final product by extraction of plant suspensions, which contributed to its widespread use of foreign pharmacological enterprises [1,2,4]. Experimentally determine the suitability of cavitation to a quality mix heavily mixed fluids opens up bright prospects not only for its use in the manufacture of lubricating-cooling liquids in the engineering industry, and so difficult to implement for blending diesel fuel with ordinary water, whereby 10 ÷ 15% reduced its consumption in engines of internal combustion, improved operating conditions of an engines [5-7].

Especially promising for improving the ecology of the environment appeared research scientists of Lviv Polytechnic National University, convincingly proved the possibility of the effective use of cavitation for wastewater disinfection of processing industries of organic and biological contaminants. These studies offer the prospect of high-quality cavitation cleaning of waste of milk processing industries, production of beer, drinks and alcohol, as well as public pools (swimming pools, water parks etc). The harmful impact of these processing facilities on the ecology of the environment very significantly not only of the lack of high-quality and low-cost technologies for treatment of waste water, but also through the very broad dissemination of these productions in almost each of the settlements. Accordingly, the contribution of these enterprises to the pollution of water resources is very noticeable. After all, wastewater of these industries without proper cleaning is discharged into nearby ponds.

Currently, the cavitation treatment of liquids and slurries on their basis most use the ultrasonic generator and hydrodynamic cavitators. Ultrasonic cavitation treatment is highly the intensity of the gravitational field generated; however, it is extremely low productivity due to rapid attenuation of ultrasonic waves in the liquid medium. Energy costs in the ultrasonic generators have been significantly - up to 500 W/dm^3, which for the most part limits the use of ultrasound by the area of laboratory research [3,8,9].

In the hydrodynamic cavitators the field of cavitation is generated by changing the speed of hydraulic flow and geometry at flow by them around solids or at moving at certain speeds solids in liquids. The most widely used hydrodynamic lobate cavitators, based on the formation of cavitation field rotating in a liquid flow at high speed of multilobate impeller. Performance of cavitation liquids processing are relatively high and become 2÷3 m^3/h. However, the intensity of gravitational field generated inside is negligible, which does not ensure quality processing of liquids, narrowing the scope of the effective use of hydrodynamic cavitators. This is due to the fact that in contrast to the ultrasonic cavitation in hydrodynamic cavitators of moving blades in fluid flow at the first stage are formed the so-called cavitational bubbles, and only after the collapse are formed the cavitation bubbles, which form the basis of the gravitational field. A significant part of the energy is consumed not on the formation of the cavitational field, saturated microbubbles, but on the formation of cavitational cavities filled with air, vapors and gases. Cavitational processing of the liquids are valuable by the neoplasms cavitational bubbles, increasing their volume, quantity and, more importantly, the energy of their collapse, and producing by these processes and effects.

Mechanisms of cavitation treatment of liquids are mostly identical, regardless of the excitation type of cavitational field. Mechanisms of cavitation in fluids based on water are the most important. In a very short period of time many stages of birth, growth and collapse of cavitational bubbles under the effect of changing air pressure in them and dissolved gases in the liquid contribute to the formation of powerful energy waves, chemical reactions and transformations in the structure of water molecules. On the base of water are formed OH radicals in the cavitational field in the liquids, which has high activity to chemical oxidative reactions. And even though the existences of these individual radicals are calculated in milliseconds, and a large number of continuous the formation of new instead enter into a chemical reaction, it contributes to an intense chemical oxidation reactions with contaminants such as organics, filling processed liquid. Wherein, microwave energy generated by collapse of cavitational bubbles destroyed membranes of microorganisms, bacteria and yeast, which is in the liquid, providing by it the decontamination of processed liquids from biological contaminants. Organics of internal content of destroyed microorganisms under the influence of radicals OH partially converted into H_2O and CO_2, partly deposited in storage of the treated liquid. Certainly, the mechanism of beneficial cavitational effects on the processed liquids is much more multifaceted and complicated. And it should be noted that a comprehensive of theoretical explanation is not created until today. But the undisputed is the fact that cavitation is able to positively influencing on the fluid, improving their quality and facilitating purchases them new positive properties [10-12].

The absence of cavitational equipment limits the scope of a broad industrial use cavitation for today, able to organically combine significant processing performance with its proper quality due to the high intensity of the generated cavitational field [13-15].

The purpose of this study is to develop vibrational cavitators of resonant action that can provide a combination of high performance and quality of cavitation exposure to the liquid.

The list of the main tasks of the studies included:

- analysis and prospects of low-frequency vibrations for excitation of cavitational fields in liquids;
- an experimental study of the conditions of origin and stability existence of the cavitational field under the low-frequency vibration;
- development of calculation methods and design of vibrocavitators of resonant action;
- experimental determination of basic technological parameters of vibrocavitation treatment
- verification of technological possibilities and suitability of vibrocavitation processing of wastewater treatment of processing industries, public pools (swimming pools and water parks), natural water.

The main advantage the firstly created low-frequency vibrocavitators is to reduce by 20÷25% of energy consumption for excitation and ensuring stability of formed cavitational fields in the liquids. This is achieved by summing to resonance of cavitation cavity, which are present in the treated liquid, as in most cases, which are the microbubbles of dissolved air and gas in the liquid, various suspended in a liquid and activate the microparticle.

It should be noted that the ability of low-frequency vibration to the excitation of cavitational fields is set for a long time. However, in normal conditions, the cavitation intensity here is very small and not very effective in the use of traditional cavitation technology. Very common variety of vibratory devices for intensification spatial movements excites the hydrodynamic cavitation of solids, such as vibrating blades. But here the effect is negligible and, for the most part, calculated by percent parts.

Tangible effect using low frequency vibrations is possible only during approaching the resonance oscillatory processes of the cavitational nuclei, which is accompanied by a rapid increase in their spatial displacements.

Like everything in the world around us, suspended in the liquid cavitational nuclei are in the continuous oscillatory motion with very high frequencies up to hundreds of kilohertz of own oscillations. It is necessary that the frequency of the external force action on them was equal or a multiple of their natural frequency for resonance summarizing of their vibrational motions, which is accompanied by a rapid increase of their spatial displacements on the order, and even more. Equality of nuclei frequencies and the external force action on them relatively easily achieved with ultrasonic cavitational treatment, where the oscillation frequency that excites cavitational surfaces of magnetostriction radiator are within the 22-150 kHz. This fact explains the high efficiency of liquids sonication.

The hydrodynamic cavitators frequency of spatial displacements in the liquid that is excited cavitation of the solids reach no more than a few hundred Hertz, which is significantly below the range of the own frequencies of the oscillations of cavitational nuclei. Therefore, about the resonance in the traditional perception of its essence is not even discussed.

However, as was shown results of our research, and there are certain reserves of the rapid intensity increase of the hydrodynamic cavitation treatment. It was found that the resonance of cavitational nuclei can be achieved even at the frequencies of the external force impact, not only equal to the oscillations frequencies of cavitation nuclei, but at the frequencies which are multiples of the resonance. This phenomenon is quite common in mechanics and is used for industrial purposes. For example, vibration and centrifugal machine for hardening treatment of parts, in planetary vibroexciter and other similar devices. The mechanism of this phenomenon is quite simple inherently and most clearly illustrated by the example of children's swings - no need to increase the amplitude of the oscillations as a swing pushed her in each of the periods of oscillation. Enough with some frequency, but the main thing is to regularly apply a force effect to the oscillating swing, and vector of which is coincide with the direction of oscillation swing. At the same time, depending on the frequency and magnitude of the external force impact, oscillation amplitude of the swing can both decrease and increase rapidly. In practice of the vibration technology these frequencies of force action on a harmonically oscillating body, contributing to summarizing the resonance oscillation system are called frequency ranges of resonance multiplicity and there are different from the resonant frequency in hundreds and thousands times. Stable in time and match the direction of displacement of the oscillating object are the main strict observances for two main requirements to them.

It was found that the principles and regularities of the multiplicity frequency apply to hydraulic objects, and in particular to suspended in liquid medium its foreign objects - air and gas bubbles, solid particles, and similar formations, i.e. to the cavitational nuclei! Experimental confirmation of this phenomenon has become a key stage for the creation of a new type of cavitation equipment and was named by us as a low-frequency vibrational cavitators of the resonance action.

Electromagnetic vibrational cavitator

Schematic diagram of the circular electromagnetic vibrational cavitator (CEVC) of the resonance action [1,2] is shown in figure 1. Figure 2 shows a fragment reproduced soundboards-disturber of cavitation with the nozzles-injectors when overflow liquid there through, which is accompanied by the formation of cavitation.

Schematic diagram of the circular electromagnetic vibrational cavitator includes loading chamber 6, the working chamber 9 and drain chamber 14, which are interconnected with the possibility of relative displacement through flexible corrugations 8 and 12. On the working chamber is fixed annular anchor 10, that is scored from a sheet metal, but camera and anchor are fixed through a cylindrical elastic rods 5, connected with the reaction mass 11, fixed on the pipes of loading and discharge chambers. Aligning to anchor 10 through cylindrical elastic rods 2 to the reaction mass is an established the stator body 4, in which uniformly on a circle is located coil of electromagnets 15 with the windings 3. Windings of the six electromagnets, which are equally spaced in a circle, connected so that they form three a two-stroke vibroexciter, which is offset between themselves for 120°.

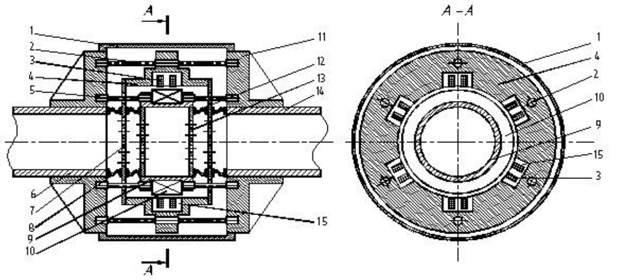

Fig. 1. Schematic diagram of the circular electromagnetic vibrational cavitator (CEVC) of the resonance action

Aligning located stator with coils and windings, and also anchor with the working chamber form an annular electromagnetic vibroexciter, which in combination with an attached to an elastic rods to the reaction mass are form the three-mass resonance oscillating system. The first of the oscillating masses is the working chamber with an anchor attached to it, the second ones is the stator with coils and windings, and the third ones is the reaction mass with massive tubes loading and discharge chambers.

The fluctuating soundboards 7 and 13 in the electromagnetic vibrating cavitators, which move in the liquid flow are the agents of cavitation, ie, solids. Their surface permeate through holes, and after it flow at the high speed formed tensile voltages of high gradient in the treated liquid. These voltages predetermine the destruction of intermolecular bonds in a liquid and the formation of cavitation bubbles from always present in the liquid cavitation nuclei, and its avalanche growth actually creates a cavitational field. The soundboards-disturbers of the cavitation 7 and 13 are hard attached to the armature and stator and over their entire area evenly spaced holes for overflow the treated liquid. Pair of soundboards attached to the anchors and the stator are symmetrically located on the inlet and outlet of the working chamber.

To intensify the disturbance cavitation when overflow through the DEC 7 and 13 of the liquid to be treated in the hole DEC pressed injector nozzle 16 with a cylindrical outer α and β spherical inner surfaces (fig. 2). The diameter of the cylindrical surface of Au = 2A and the inner surface of the spherical radius R = 2A equal magnitude, that is, double the value of the amplitude fluctuations A deki. At the intersection with the end plane of γ-nozzle injector 16 inner spherical surface defines an aperture β for the liquid overflowing whose diameter equable Prior = A. This nozzle opening 16 faces the direction opposite to the direction of flow of the liquid being treated (fig. 2). The distance between adjacent holes in dekah exactly double the value of the oscillation amplitude, that is, l = 4A. From foreign objects to the oscillating electromagnetic exciter systems protected protective cover 1 (fig. 1)

Job vibrating electromagnetic cavitator follows. Loading chamber through pipe 6 into the working chamber 9 at a slight pressure or samotokom fed process liquid. Simultaneously, the winding coils 3 15 series of electromagnets or anticlockwise energized. The electromagnets are in the same sequence alternately attract the armature to the treated liquid filled working chamber, bending the thus toward each other elastic cylindrical rods 2 and 5. The deflection and elasticity of the cylindrical rods 2 and 5 are designed so that they eliminate the collision between the armature and stator a. Alternate pulling anchor to the adjacent stator coils is transformed into a circular directed antiphase oscillations of two resiliently mounted oscillating masses, namely the anchor to the working chamber and the stator. These oscillations occur with certain calculated amplitude and frequency equal to the power supply to the electromagnetic coil ring usually 50 Hz.

Together with oscillating masses plane-parallel circular antiphase movement in the chamber is carried out and attached to them deki 7 and 13 holes, crossing the stream continuously flowing into the chamber liquid to be treated. With the recommended oscillation amplitude DEC 2,0 ÷ 2,5 mm and a frequency of 50 Hz rate at which the fluid flow crosses DEKA, is 0.65 - - 0.8 m / s, and the velocity of the relative movement of two adjacent DEC, which fluctuate in antiphase, twice, i.e. 1.3 - - 1.6 m / s. With the same rate of the treated fluid stream flow through the nozzle dekah.

This velocity of liquid jet is sufficient to form air cavitation cavern from the dissolved air and gases present in the treated liquid. When moving the air cavities along the inner surface of the spherical nozzle injectors 16, pressure inside the caverns is growing up rapidly, increasing their volume, resulting in creation of shock wave impulses on the output of the nozzle. Action of shock wave impulses on the nuclei of cavitation present in the liquid is accompanied by instantaneous nucleation, expansion and subsequent collapse of cavitation bubbles. Evenly spaced holes in the soundboards provide uniform intensity of cavitation field throughout the cross-sectional area of the working chamber thus, achieving the uniformity of the liquid treatment.

Due to the symmetrical arrangement of soundboard cavitation disturbers, the fluid flowing through the working chamber 9 undergoes double cavitation treatment. After double cavitation treatment in the working chamber, the fluid is released through the output chamber 14 for the subsequent target use.

Regulation of the quality of the liquids treated in the vibrational electromagnetic cavitator with resonant action is performed by adjusting the intensity of the generated cavitation field in liquid, which depends on the oscillation amplitude **A** of soundboard cavitation disturbers, frequency of these oscillations, and hole diameter $\mathbf{D_0}$ for overflowing liquid. The amplitude of soundboard oscillations is adjusted by changing the value of current supplying electromagnetic coils, which changes the force of attraction between the armature and stator electromagnets, which, in fact, determines the value of spatial displacements, that is, the scope and the amplitude of the oscillating movement of soundboard cavitation disturbers. Soundboard oscillation frequency is adjusted by regulating the frequency of the thyristor regulation circuit of the frequency of voltage supplying the electromagnetic coils, which changes the attraction frequency between armature and the stator electromagnets, i.e. the frequency of spatial displacements of rigidly connected to the armature perturbing soundboard cavitation. Optimum values of the amplitude and oscillation frequency are selected empirically depending on the physical parameters of the processed liquids: the density, viscosity, surface tension, and so on. Special attention during the selection of technological parameters of vibrational cavitation treatment is spared to the choice of the soundboard vibrational frequencies, trying to find them as close as possible to the multiple intrinsic frequencies present in a particular treated liquid with microbubbles of dissolved gases and air, playing the role of cavitation nuclei. This ensures the implementation of the cavitation treatment in the so-called resonant mode with minimal energy losses.

Calculation of elasticity of oscillating systems, power of the electromagnetic drives, and their structural elements (shape and dimensions of the electromagnets, a cross-sectional area, number of coils and so on) is performed by conventional methods for calculation of vibrational machines with electromagnetic drives [3].

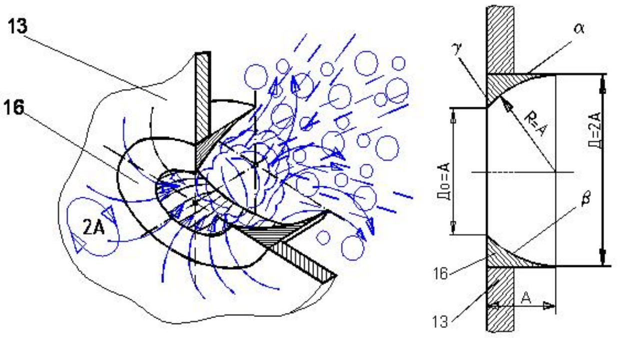

Fig. 2. The soundboards-disturber fragment of the cavitation with the tubes-nozzles at the liquid overflow therethrough and the formation of cavitational cavern (the numbering of the positions is respectively to fig. 1)

Devices for vibrational resonant cavitation treatment of liquids include two groups of varying regulation parameters, ensured with quality index of cavitation treatment, which are the group of constructive and the group of technological parameters.

To the group constructive parameters belong:

- vibrational frequency of soundboard cavitation disturbers, which is regulated by the frequency regulator installed in the remote control console, for example, models AFC - 120;
- oscillation amplitude of soundboard cavitation disturbers, which is regulated by the power and constructive parameters (the gap between the armature and stator) of electromagnetic drives and the rigidity of the elastic system (bars 2 and 5) of the soundboard suspension;
- the direction of vibrations of soundboard cavitation disturbers (along or across the treated fluid flow), which is ensured by locations of the electromagnetic drives.

The main task of changing the constructive parameters here is to change the velocity and direction of spatial displacement of soundboard cavitation disturbers in the fluid flow, which ultimately affects the range of vibrational resonant cavitation perturbations.

To the group of technological parameters here belong:

- pressure and velocity of the liquid treated in the zone of cavitation treatment, which are adjusted by the flow rates (the pump and the throttle flow line) of supplying liquid to the working zone;
- the variety, quantity and pressure of the gas or air, concomitant to treatment, which are adjusted by throttling the gas supply line;
- the amount of available in the treated fluid cavitation nuclei, which are adjusted by the amount of supplied gas to the treatment zone.

The main objective of the changes of technological parameters here is the influence on the energetic state of the treated liquid, the influence on the duration of this treatment.

Consequently, the changing of constructive and technological parameters effectively influences on the strength of the treated liquid, its ability to the perturbation and stable existence of the cavitation phenomena therein. It also influences on the intensity of the cavitation field generated therein, which ultimately determines the quality of cavitation treatment of liquids.

Mathematical formalism

The feature of vibrational cavitators, as well as the cavitators of any other type, is the need to ensure certain energetic influence on the treated liquid medium. This level of energetic influence, which is accompanied by a perturbation of cavitation phenomena in the fluid that initiate an effective behavior of specific physical processes and chemical reactions in the treated medium. From the positions of molecular physics, the creation of certain preconditions for the appearance and subsequent growth of the existing in the liquid cavitation nuclei of cavitation field saturated with cavitation bubbles is governed by a dimensionless complex Reynolds **Re**, so-called Reynolds number **Re**, connecting the changes of the characteristic flows of fluids of a certain density and viscosity with a change of velocity and pressure of fluid. The critical Reynolds number **Recr** can be interpreted as a parameter that determines the threshold of the nucleation of cavitation in the liquid substance. In mathematical terms, the Reynolds number **Re** is given by [4]:

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

where: ρ – medium density, kg/m^3; υ – velocity of fluid flow, m/s; μ – dynamic viscosity of a medium, Pa·s; here $\nu = \mu/\rho$ – kinematic viscosity, m^2/s; L – characteristic linear size (for a selected equipment), m.

The Reynolds number **Re** in a certain way reflects the relationship between the nature of the liquid flow and its velocity. For example, for numerical values in the range 2000 ≤ **Re** ≤ 20000, the overflow of liquids of small densities and viscosities, is usually performed in a laminar mode; at higher numerical values laminar mode is changed to turbulent mode. The dimensionless Reynolds number **Re** governs also the appearance of cavitation processes in the fluid flow. The numerical values of dimensionless Reynolds numbers **Re**, for which the cavitation field self-appears in a liquid flow, is called the critical Reynolds number **Recr**. Their values are caused by a certain parameters of the fluid as its density and viscosity, pressure and fluid flow rate, and also the gradient of intermolecular stressed state in the fluid formed by these parameters.

For liquid substances with density and viscosity close to the density and viscosity of water, the critical Reynolds number **Recr** is usually slightly exceeds the value of $(1{,}5-2{,}0)\cdot 10^5$, so $\mathrm{Re} \geq (1{,}5-2{,}0)\cdot 10^5$ [4].

Consequently, substituting in equation (1) the numerical values of the parameters of the treated liquid and the critical Reynolds number **Recr**, the critical rate of oscillating movements of executive bodies of vibrational cavitators required for perturbation can be determined from the dependence:

(2) $$V_Д^* = \frac{\mu \cdot \mathrm{Re}_{кр}}{\rho \cdot L_д} = \frac{\nu \cdot \mathrm{Re}_{кр}}{L_д},$$

where: L_d – the total adduced size of the circumferences of holes of oscillating soundboard, m.

In the case of simultaneous use on the working zone of several soundboards, which vibrate in antiphase, each velocity of the oscillating movements $\mathbf{V_d}$ can be reduced by the total amount of these soundboards **n**, i.e.

(3) $$V_d = \frac{V_{d^*}}{n}.$$

The average velocity of the oscillating movement of any vibrating bodies, including soundboard cavitation disturbers, so-called vibrational rate, is limited by the frequency **f** and amplitude **A** of their oscillations [5]. Therefore, choose, for example, the oscillation amplitude **A** and equating a velocities **Vc = Vd***, the required frequency of soundboard oscillations will be

(4) $$f=\frac{V_к}{2\cdot\pi\cdot A}=\frac{\mu\cdot \mathrm{Re}_{кр}}{2\cdot\pi\cdot A\cdot\rho\cdot L_o}=\frac{\nu\cdot \mathrm{Re}_{кр}}{2\cdot\pi\cdot A\cdot L_o},\frac{1}{c}.$$

Tractive force F_T of a drive, whereby oscillating soundboard in its motion overcomes the resistance of the treated liquid, proportionally to the total amount of the pressures $\sum P_c$ on oscillating soundboard, to the total surface area $\sum S_0$ of the holes for liquid overflows in an oscillating soundboard, and to the angle of inclination β of the oscillating soundboards to the direction of flow of treated liquid, i.e.

(5) $$F_T=\left(\sum P_c\right)\cdot\left(\sum S_o\right)\cdot\sin\beta.$$

In the case of conventional single- and double-mass resonant vibrational constructions, electromagnetic driving force of vibrational disturbers is calculated by the formula [3,5]:

(6) $$F_T=\frac{M_{св}\cdot\omega^2\cdot A_{от}}{\lambda\cdot z^2},$$

where *Mсв* – so-called adduced oscillating mass, which, in this case, is a total oscillating mass of the working chamber and includes mass of armature of electromagnetic vibrational drove $\mathbf{m_a}$, adduced mass $\mathbf{m_{el}}$ of elastic oscillating system, mass $\mathbf{m_f}$ of a treated liquid with density **ρ** in the working chamber with volume **V**, mass $\mathbf{m_d}$ of oscillating soundboard with holes for treated liquid overflow together with fasteners sealing corrugation, i.e.

(7) $$M_{св}=m_я+m_{упр}+m_р=m_я+m_{упр}+\rho\cdot V;$$

$\omega=2\cdot\pi\cdot f$ – circular frequency of cavitation disturber oscillations; **f** – oscillation frequency of armature of electromagnetic drive; $\mathbf{A_r}$ – relative amplitude of oscillations of oscillating system.

Here $\lambda=\frac{1}{\sqrt{\left(1-z^2\right)^2+4\cdot\gamma^2\cdot z^2}}$ – dynamic coefficient, where the value of resistance index **γ** for a steel elastic system without constructional hysteresis **γ** = 0.004 ... 0.006; for rubber elastic systems **γ** = 0.1 ... 0.15. **z** – coefficient of resonant adjustment.

Since the energy consumed for carrying out any technological process, including the process of cavitation water treatment, can be determined from the relation $E_{об}=N\cdot t,$ where **N** – drive power, **t** – the duration of treatment, the value of the specific energy of the cavitation process can be calculated from the relationship

(8) $$\varepsilon=\frac{E_{еф}}{V_p}=\frac{N}{V_p}\cdot t=\frac{E_{об}-E_н}{V_p}=$$
$$=\frac{N\cdot t-m\cdot c\left(T_k-T_0\right)}{V_p}=$$
$$=\left[N-m\cdot c\left(T_k-T_0\right)\right]\cdot\frac{t}{V_p}.$$

where V_p denotes the volume of treated liquid, dm^3.

The part of the kinetic energy that is converted into thermal energy $\mathbf{E_n}$ can be determined experimentally performing temperature measurement of the liquid during its processing

(9) $$E_н=m\cdot c\left(T_k-T_0\right)\tau,$$

where: m – mass of liquid medium treated in the chamber, kg; c – its heat capacity, J/(kg·K); T_f – temperature of a medium after the treatment, °C; T_0 – initial temperature, °C; τ – time of treatment, s.

The efficiency η of vibrational cavitation treatment of liquid is equal to

(10) $$\eta=\left(\frac{E_{еф}}{E_{заг}}\right)\cdot 100\%=\frac{1-E_н}{E_{заг.}}\cdot 100\%=$$
$$=\frac{\left[N\cdot t-m\cdot c\left(T_k-T_0\right)\cdot t\right]}{\left(N\cdot t\right)}\cdot 100\%=$$
$$=\frac{1-\left[m\cdot c\left(T_k-T_0\right)\right]}{N}\cdot 100\%.$$

Experiment

Experimental verification of technological possibilities of vibrational resonant treatment was carried out on wastewater of recycling industry, on water purification of public pools, as well as on the water of natural reservoirs from the pollution by cyanobacteria [6,7].

As test samples of wastewater recycling industry, the samples of milk processing plants and brewing industry were used. Disinfection cavitation treatment of these wastewater was carried out in the closed cycle process on a pilot vibrational resonant cavitation setup with the working chamber volume of 1.5 dm^3 at cavitation disturber oscillation frequency of 74÷75 Hz and amplitude of 1.0÷1.5 mm.

It was found that the cavitation treatment of wastewater of milk processing plants provides 97÷98% disinfection from the dominant so-called lactic bacteria, and 92÷93% removal of organic pollutants. The supplied performance of the experimental setup is in the range 90 ÷ 100 liters per hour. However, there is no significant influence on the concentration of the present in this wastewater lactic acid, which banefully affects on the acidity of the water and soil during the milk plants discharge into the natural environment.

During the cavitation cleaning of the brewing industry wastewater, contaminated mainly with brewers' yeast, septic tanks were included in the technological circuit of flow supply and discharge of the treated water, in which cavitation treated wastewater was desilted to separate it from the residues of the yeast bacteria destroyed by cavitation. After settling and separation of the liquid and the yeast residues, the liquid was filtered and re-send to the cavitation treatment. It was found experimentally that the effect of the cavitation field very actively destroys yeast cells. It can be explained, obviously, by the size of yeast cells, more developed surface, in comparison with other bacteria, and consequently, the more intense influence on them of the energy released in the liquid medium by collapsing cavitation microbubbles. As a result, the efficiency of the cleaning treatment here is quite high. It is approximately twice higher the performance of milk plant wastewater treatment, and for studied experimental setup was 200÷250 dm^3/h.

Of course, that for such large-scale production as the industrial wastewater treatment on the basis of our experimental setup more powerful vibrational cavitators with resonance action can be created, the cleaning performance of which will exceed in dozens or even hundreds of times the performance of the experimental setup [7].

Another effective vibrational resonant cavitation treatment is for purification and preparation of water for public pools. Nowadays, during the water preparation for the pools, ozone water treatment, are used instead of chemical treatment on the basis of chlorine. Also, its cleaning with hydrogen peroxide or sodium hypochlorite, generated in electrolysis equipment of various models, is used. A common drawback of all these modern methods of water cleaning is the high cost of water treatment chemicals. The most promising from the standpoint of the quality of water purification provided here is certainly the electrolytic cleaning. However, its widespread use is prevented by not so high cost electrolysis apparatus, but considerable energy consumption during their operation. For example, the most commonly used model for water purification is electrolysis unit "Sivash" EGR-1000, which consumes up to 10 kW of electricity. And this despite the need for a minimum of two water cleaning units for qualitative water preparation for a mid-size pool with a volume of 3.5-5.0 thousand cubic meters of water. So high energy consumption has a negative effect on the costs of services.

We experimentally tested the improved technological scheme of pool water cleaning combining electrolysis and vibrational cavitation cleaning of water. Under this scheme, contaminated water before the cleaning by sodium hypochlorite produced in the electrolysis unit "Sivash" EGR-1000, is subjected to a prior cavitation cleaning by vibrational resonant cavitators, the total power of the drive does not exceed 3 kW. This improves the quality of the water structure and its cleaning, and also by 40 ÷ 45% reduces energy consumption for the water treatment process. It is ensured by the fact that the cavitation treatment of polluted water effectively disinfects it from the biological and organic pollutants, including urea. This allows to halve the operation of the energy consuming electrolysis units.

Vibrational resonant cavitation treatment of water from natural reservoirs was found to be quite effective, which is used for growing juvenile fish, drinking and feed preparation for livestock sector, during the rural water supply. It can be explained as the cavitation treatment of water not only purifies it from the biological and organic pollutants, but also improves water structure, transforming it from a cluster structure to the monomolecular state, characteristic for the spring water. As it is well known that water in a monomolecular state is better absorbed, not only plants, but also by living organisms, beneficially effect on the digestive and circulatory systems.

Conclusions

1. A new method of vibrational low-frequency excitation of cavitation phenomena (processes) in water-based liquids and equipment for its realization were created. A distinctive feature of the vibrational excitation of cavitation is the energetic effect on the fluid flows by cavitation disturbers at their oscillation frequencies multiple to the natural frequencies of the suspended in liquids cavitation nuclei.
2. Excitation conditions of cavitation processes by low-frequency vibrations were determined and theoretically proved. The relations for calculation of the velocity of spatial displacement of cavitation disturbers in the fluid flow, the frequency of oscillation, as well as the main parameters of the drive of vibrational resonant cavitators were shown.
3. Compared with ultrasonic cavitators, which in the vast majority inherent a point magnetostrictive cavitation disturber, vibrational cavitators provide uniform distribution of the cavitation field intensity throughout the cross-section of the working chamber, thus, the uniformity of the liquid treatment.
4. Comparing with hydrodynamic cavitators, vibrational resonant cavitators provide 25÷30% increase of the intensity of cavitation field, hence, proportional productivity increase of cavitation liquid treatment.
5. Experimental verification of technological possibilities of vibrational resonant cavitation treatment proved its high efficiency of wastewater cleaning for agricultural product industry, for water purification of natural reservoir and public pools.

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