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WATER TREATMENT AND DEMINERALIZATION TECHNOLOGY

Enhancing the Efficiency of Ultrasonic Wastewater Disinfection Technology

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Abstract—Experiments have confirmed that the efficiency of wastewater disinfection using the ultrasonic cavitation is ensured by taking into account the size and structure of microorganisms. The intensity of ultrasonic vibrations is shown to influence the specified process. The recommendations for constructing ultrasonic cavitators are provided that ensure a high intensity level of ultrasonic vibrations in process liquid volume.

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INTRODUCTION

Many processes in industry and everyday life make use of liquid media that during their service can be subjected to contamination with microbes, which are harmful and dangerous to human health. Such problem is encountered in metal working industry, while using the lubricating and cooling liquids having a direct contact with microbes and also in discharge of the process wastewater from livestock enterprises, meat-processing factories, public catering places, medical purpose laundry enterprises, etc. The problem of disinfection is even more acute in conditioning of drinking water, and also in food production processes because it materially affects the quality and consumer properties of foodstuffs. The selection of process liquid treatment is determined by the type and degree of pollution. The state-of-the-art technologies of water treatment are based on using mechanical, chemical, biological and physical techniques that result in the removal of different types of mechanical impurities, improvement of water quality and enhancement of epidemiologic security. Disinfection is the final and mandatory stage of water treatment that ensures its decontamination from pathogenic microflora [1].

Up-to-date and most advanced methods of microbial inactivation in water include cavitation treatment featuring a specific technique of cavitation excitation. The analysis of modern studies on water disinfection using the hydrodynamic cavitation in static- and dynamic-type rotary-pulse plants and also its possible combination with other physicochemical methods of microflora inactivation [2–7] confirms the low efficiency of these plants stipulated by the following disadvantages:

– high or, conversely, insufficient energy of cavitation cavities that are present in small quantity in cavitation region as compared to a considerable quantity of microorganisms non-uniformly distributed in the process volume;

– large sizes of cavity pockets produce a shielding effect and prevent the uniform distribution of shock waves appearing at the collapse of these cavity pockets;

– small amount of high-power cumulative jets formed in the process of collapsing of cavity pockets near the surfaces (surface of cavitation chamber, the surface of adjacent cavity pocket or microorganisms);

– the need of creating a high-cost hydrosystem for obtaining high-speed liquid flow.

The use of ultrasonic (US) cavitation excited at the expense of discrete-pulse injection of acoustic energy into liquid makes it possible to eliminate many of the specified drawbacks and ensure a high degree of water disinfection [8].

Spatial discreteness of injected acoustic energy in the form of high-power but short pulses contributes to decontamination of water at small consumptions of energy. In this case, the microscopic cavity bubbles formed in large numbers represent high-energy sites that are uniformly distributed in the treated volume in the close proximity to microorganisms.

The purpose of this paper is to determine the regimes of ultrasonic cavitation treatment of aqueous media making it possible to attain a high efficiency of microbial inactivation.

EXPERIMENTAL

The tests were conducted in two stages that differed by the technique of obtaining water samples containing microorganisms.

At the first stage, the process wastewater from the livestock breeding complex sampled after the sewage treatment plant were used as a material for investigations. The initial samples were taken before each treatment plant and immediately at its outlet.

At the second stage, the medium was simulated by the introduction of different kinds of microorganisms into sterile water for obtaining the so-called "microbial suspension". The investigations were conducted choosing the following museum strains of microorganisms: *Escherichia coli* ATCC No. 25922 (specific index of water fecal pollution), *Pseudomonas aeruginosa* ATC No. 27853 (it is ubiquitously spread and separated from soil, water, from plants and animals), *Bacillus stearothermophilus* BKM-B-718, vegetative and spore forms (spore-forming organism with high resistivity), and *Staphylococcus aureus* No. 209-P (sanitary representative microorganism). The simulation of natural pollution of water was conducted in laboratory conditions using the turbidity standard and further ten-fold dilution of microbial suspension in sterile water (the amount of microorganisms in 1 cm^3 was 2×10^3 CFU).

The determination of protozoa in water samples implied the visual analysis under the microscope (control of five points and summation of results obtained).

The degree of bacterial pollution of water was assessed by determining the total bacterial count (TBC), i.e. total number of colonies that were grown in nutrient medium during 24 h at 37°C; the results of count of grown colonies were compared with control.

The value of microflora inactivation degree I (n_0/n, where n_0 is CFU after US-treatment, n is CFU before the treatment); I is a function of two parameters:

$$I = f(\tau, P),$$

here τ is the water treatment duration, min; and P is the power consumption, W.

The domain of determination of factors: $200 \le P \le 600$, $1 \le \tau \le 6$.

The determination of target function involved the need of obtaining a regression second-order model with the effect of first-order interaction:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{11}{}^2 x_1 + b_{22}{}^2 x_2,$$

where b_0, b_1, b_2, b_{12}, b_{11}, b_{22} are the regression coefficients.

The number of repeated tests corresponded to recommendations of paper [9]. Regression coefficients were determined by the second-order method of central composite rotatable design [10, 11] based on the full factorial experiment of form 2^2.

The nutrient inoculating medium was selected depending on the strain of microorganism: Endo medium for *E. coli* ATCC no. 25922 and *P. aeruginosa* ATC No. 27853, agar-meat infusion for *Bac. stearothermophilus* BKM-B-718, and egg yolk agar for *St. aureus* No. 209-P.

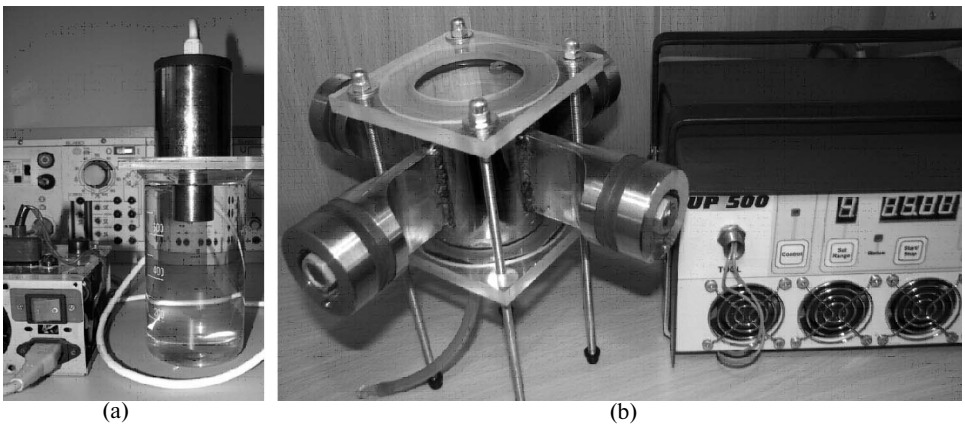
The cavitation treatment of water test samples was conducted in experimental setups using a high-amplitude cavitator drive (Fig. 1a) and ultrasonic tubular cavitator (Fig. 1b). The correction and variation of parameters of the setups was performed by a digital control system.

RESULTS AND DISCUSSION

Several groups of microorganisms (bacteria, viruses, fungi, and protozoa) capable of provoking different kinds of deceases are common in water and process fluids. The cellular texture is the same for the majority of prokaryotes. It represents a set of main components, such as cell wall, cytoplasmic membrane, cytoplasm with inclusions, and nuclides. The cell texture may include additional structures: capsule, flagellums, etc. Differences between groups of microorganisms mostly involve their geometrical dimensions, shape and structure.

It is plain to see that the high efficiency of disinfection process of liquid media using the US-cavitation can be achieved by taking into account the size and structure of microorganisms. In this connection, at the first stage of investigations we studied the impact of US-cavitation on protozoa. Table 1 presents the results of the

treatment of process wastewater from livestock breeding complex by using the high-amplitude cavitator (see Fig. 1a).



(a) (b)

Fig. 1. Experimental setups: high-amplitude cavitator (a) and tubular cavitator [12] (b).

Table 1. Results of the treatment of wastewater from the livestock-breeding complex using the high-amplitude cavitator

Sample number	US-treatment, s	Microorganisms	Size, μm
1	0	Roundworm eggs (5 pcs)	40–50
2	0	Amoeba (2–3 pcs)	20–30
3	0	Roundworm eggs (1 pc)	40–50
1	6	Amoeba (1 pc)	20–30
1	12	Roundworm eggs (5 pcs)	40–50
1	30	Not detected	–
2	30	Ditto	–
3	30	–	–

Note. 1—denotes the sample taken before the first stage of treatment; 2—denotes the sample before the second stage of treatment; and 3 is the sample at the outlet of the treatment plant.

The analysis of findings indicates the dependence of the protozoa cell disruption on the US-treatment duration.

Thus, given the small productive capacity of water treatment, it was expedient to use an ultrasonic high-amplitude cavitator with vibration rate transformer having intensity up to 20 W/cm^2 at resonance frequency of 22 kHz.

The effective high productive capacity schemes of in-stream water treatment imply the maximum possible reduction of water treatment duration by increasing the US-wave intensity level introduced into liquid. However, the US-oscillations with intensity > 18–20 W/cm^2 are inexpedient because a two-phase cavitation layer formed at the radiating surface of US rate transformer scatters and absorbs US-energy preventing its passage into the liquid volume subjected to treatment. That is why it is proposed to introduce low-intensity US-oscillations into liquid, while the enhancing of vibration intensity in the bulk of treated water to the high required level could be ensured at the expense of the focusing properties of cavitator surface. It can be achieved by using a tubular cavitator having the piezoelectric resonant actuators of longitudinal displacements with knife-shaped rate transformers mounted on the cavitator outer surface [12, 13].

Analytical relationships for velocity potential (Φ_m) and sound pressure (P_m) occurring in liquid filling the tubular vibrator during the passage of deformation sound wave under the condition of liquid flow continuity have the form [12, 13]:

$$\Phi_m(r,\varphi,z,t) = A_m J_m(\mu_p r)\cos m_T\varphi \cdot e^{J\gamma_p z}\sin\omega t;$$

$$P_m(r,\varphi,z,t) = A_m \rho\omega J_m(\mu_p r)\cos m_T\varphi \cdot e^{J\gamma_p z}\cos\omega t,$$

where r is the radius-vector, φ is the polar angle, z is the coordinate along the vibrator axis; A_m is the constant determined by boundary conditions, $J_m(\mu_p r)$ is the cylindrical m-order Bessel function, $\omega = 2\pi f$ is the circular frequency, $\gamma_p = \sqrt{\frac{\omega^2}{c^2} - \mu_p^2}$ ($\mu_p{}^2$ is a constant and c is the sound velocity in liquid); $m_T = 0, 1, 2, 3, \ldots$

These expressions make it possible to obtain a pattern of the sound pressure distribution across the tubular cavitator section, in particular for zero vibration mode (Fig. 2).

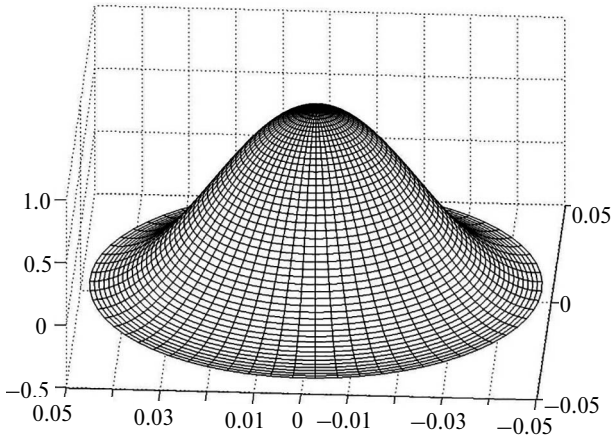


Fig. 2. Distribution of acoustic pressure across the section of tubular cavitator at radial vibrations of wall.

Graphical solution illustrates the focusing, i.e., concentration of US-energy along the vibrator axis and its minimal level on the internal surface of cavitator that corroborates the correctness of choosing the parameters and regimes of cavitation treatment of water aimed at the inactivation of microorganisms.

The setup with tubular vibrator (see Fig. 1b) excited at zero vibration mode makes it possible to materially enhance the intensity of US-treatment. Investigations on microorganism inactivation were performed for determining the efficiency of tubular cavitator. Similar to the previous case, we started with assessing the impact on the protozoa representatives. The comparison of states of microorganisms before and after treatment is illustrated in Fig. 3.

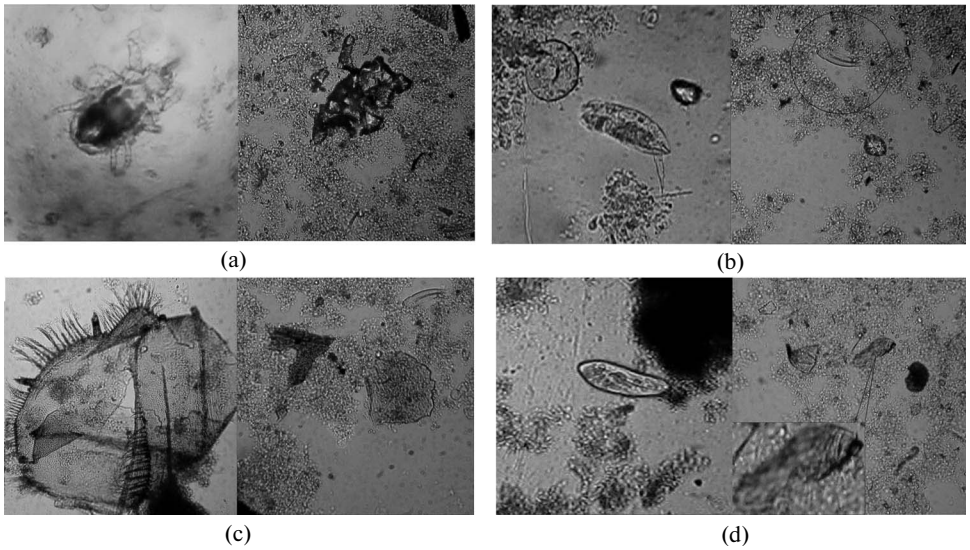


Fig. 3. The state of microorganisms before and after the treatment, respectively, (power consumption is 600 W, and the exposure time is 5 s): crustaceans (a), rotifers (b), gastrotricha (c), and infusoria (d).

The analysis of findings confirms that the introduction of high-intensity US-vibrations into liquid results in a shorter time required for attaining the necessary level of microbial inactivation.

The efficiency of US-cavitation impact on the viability of museum strains of microorganisms was estimated by the exposure of microbial suspension to the 200 W irradiation during 5 min (Table 2).

Table 2. Results of the US-treatment impact on the viability of museum strains of microorganisms

Culture	Number of microbial cells, CFU	
	before treatment	after treatment
E. coli ATCC No. 25922	210	200
Bac. Stearothermophilus BKM-B-718, (vegetative form)	200	196
Ditto, (spore form)	180	160
P. aeruginosa ATC No. 27853	190	176
S. aureus No. 209-P	168	156

It was revealed that under the specified test conditions microorganisms preserved their viability and biochemical properties. This is a clear indication that the inactivation of bacteria, unlike protozoa, requires a higher intensity level of US-vibrations.

For elucidating the impact of various power US-treatment on the breakdown of microorganisms, the experiments were carried out aimed at revealing that the dependence of the microflora inactivation degree I on the treatment duration τ and power consumption P could not be adequately described either by linear or quadratic regression models. Therefore, it was necessary to determine the dependence of the latter on impact factors raised to fractional degrees [11]:

$$I = f(\tau^{2.312}, P^{0.9622}).$$

The regression equation for the response function (the value of microflora inactivation degree) has the following form in accordance with the conducted multifactorial experiment:

$$I = 2.636 - 0.2471\tau^{2.312} - 0.008704P - 6.905 \times 10^{-6}\,\tau^{2.312}\,P^{0.9622} + 2.619 \times 10^{-4}\,\tau^{4.624} + 1.003 \times 10^{-5}\,P^{1.9244}.$$

It has been established that the Fisher criterion hypothesis regarding the adequacy of regression model can be considered correct with 95% confidence. As revealed by using the Student criterion, the microflora inactivation degree is more dependent on the power consumption and less dependent on the treatment duration.

The application software package (MathCAD) was used to optimize the response function by its minimization. It has been found out that the lowest degree of microflora inactivation (0.012) is ensured at the following optimal parameters: $\tau = 5.1$ min and $P = 515$ W. The surface of the target function response in the plane of specified parameters makes it possible to clearly illustrate the relationships obtained (Fig. 4).

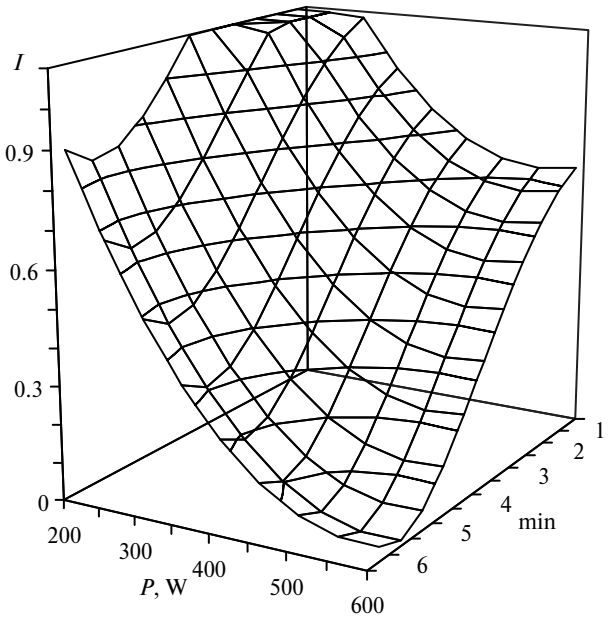


Fig. 4. The surface of the target function response.

Additional investigations were conducted for studying peculiarities of the impact of treatment parameters on different museum strains of microorganisms (Fig. 5). The findings show that the disinfection can be expediently carried out at $P = 500$ W. Further rise of the ultrasonic intensity does not result in appreciable reduction of the treatment duration, i.e., it is power-hungry.

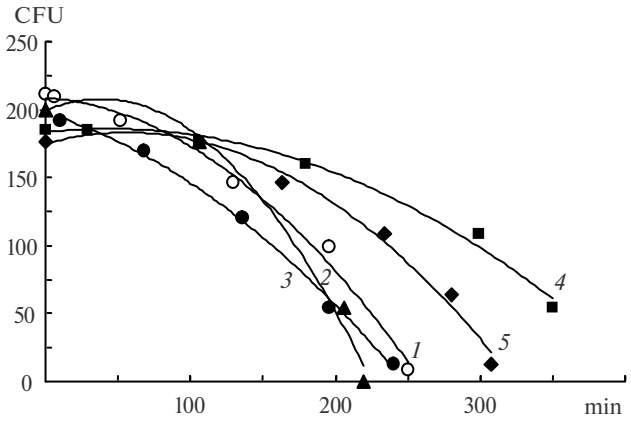


Fig. 5. The relationship of the inactivation of the museum strains of microorganisms as a function of the treatment duration at $P = 500$ W: *E. coli* (*1*), *Bac. Stearothermophilus* (vegetative form) (*2*), *P. aeruginosa* (*3*), *Bac. Stearothermophilus* (spore form) (*4*), and *S. aureus* (*5*).

The mechanisms of ultrasound bactericidal action described in papers [14–16] are related to the shock waves, pressure gradients, local rise of temperature, chemical reactions, etc.

Cavitation disintegration of microorganism cells under conditions of vapor–gas cavitation is stipulated by a complex of the mechanical and chemical actions. According to paper [17], the water disinfection under the impact of mechanical factors occurs in accordance with a first-order relationship, while the inactivation of microorganisms under the impact of chemical active compounds proceeds in accordance with a second-order relationship. The energy level introduced for the US-treatment of liquid media significantly affects the size of cavitation bubbles and, consequently, determines the quantitative changes of microflora.

In our opinion, the main mechanism of inactivation action of high-intensity US-cavitation on microorganisms representing, mostly, liquid dispersions consists in the fact that small-size bubbles formed during the US-cavitation are capable of being located in the close proximity to microorganisms. It results in high-power cumulative microjets formed during the bubble collapsing that are directed to the surface of microorganisms [18, 19]. These cumulative jets produce a disintegrating effect on cellular wall and the cell as a whole. A large number of small-size cavitation bubbles during US-cavitation contributes to uniform saturation with bubbles of the liquid volume under treatment providing for a high efficiency of disinfection. The other effects accompanying the US-cavitation phenomenon, such as spherical waves, high local temperatures and pressures, chemical compounds, in particular hydrogen peroxide and hydroxyl radicals also participate in the process of microbial inactivation, however their impact is auxiliary and less tangible.

CONCLUSIONS

An enhanced degree of liquid media US-disinfection and the extension of spectrum of inactivated microorganisms are attained by the rise of intensity of US-oscillations in the process volume of liquid under treatment. The quadratic exponential regression equation makes it possible to adequately describe the dependence of the target function (degree of microflora inactivation) on the main parameters of exposure. This equation can be used for mathematical simulation of microflora inactivation. The target function in accordance with the Student criterion depends on the power consumption in a larger degree as compared to its dependence on the duration of water treatment. The required high intensity level of US-oscillations in liquid can be expediently attained by using the focusing features of radiating surface of cavitator. We studied the parameters providing for the high efficiency of water disinfection process using US-cavitation due to the proper regard for sizes and the structure of microorganisms. In this case, the required energy level of US-oscillations in aqueous medium is determined by matching the parameters of US-cavitator and the process medium.

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