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MECHANISM AND KINETIC REGULARITIES OF INACTIVATING EFFECTS OF CAVITATION ON MICROORGANISMS

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Abstract. Disinfective action of physical-chemical effects accompanying hydrodynamic cavitation on the microorganisms sanitary indices in water has been studied. Disinfection kinetics was found to be dependent on the cavitation field characteristics and the microbes population. Based on the structural-morphological investigation of the *E.coli* bacteria it was found that antimicrobial effect is obtained due to the mechanical rupture of cells and chemical disinfection, which results from the hydroxyl radicals and hydrogen peroxide effect. Mathematic model that allows predicting the disinfection result under the hydrodynamic cavitation has been developed. The effect of chemicals on *E.coli* microorganisms under hydrodynamic cavitation has been investigated. Adding of $AgNO_3$ or hydrogen peroxide in the cavitation installation makes it possible to reduce the disinfection time and to decrease the chemical oxides concentration by 50–70 %, which is caused by the synergism effect.

Keywords: hydrodynamic cavitation, disinfection, microorganisms, kinetics.

1. Introduction

At the present stage of engineering and technology development one of the most promising branches of investigation is development of techniques for providing proper water purification and disinfection. Water chlorination, which was popular in the past during the infectious diseases epidemics, does not meet the demands of water purification as it worsens water quality and ruins water reservoir self-purification functions. That is why, the choice of optimum eco-friendly disinfection techniques are of great economic importance. Among the routine methods of water disinfection the most promising ones, as compared to chlorination, are those based on the use of ozone, hydrogen peroxide, as well as silver and cuprum ions. Ozonation allows not only to disinfect water but ensures its deodorization. However, simultaneously with the high level of disinfection (99.0–99.99 %), reactivation of microorganisms is testified, which leads to the secondary bacteria growth [1]. In the hydrogen peroxide disinfection high enough concentrations of reagents (6 % hydrogen peroxide) are used. High cost and poor availability of these reagents make the field of its application narrow [2]. Cuprum and silver ions were found not to be used widely either, although they possess enough good antimicrobial effect, which ensures the preservation effect [1, 2]. An alternative to the chemical methods of influence on the pathogenic (bacterial) flora are the physical ones, such as electro-treatment, ultraviolet treatment, glow discharge, and cavitation [2-8]. They are of interest both separately and in combination with the chemical reagents. That is why, the hybrid application of different disinfection agents could help to solve the problem of qualitative water supply.

The authors have presented data on the disinfection by cavitation which is generated by ultrasonication, hydrodynamic effects or electro-impulse discharges. Nowadays the most investigated and studied are the processes of water disinfection under ultrasound cavitation [2, 8, 15, 20], but this method is suitable only for the treatment of small water reservoirs, which is explained by the low efficiency and great power consumption of this process. The efficiency of this method is explained by the authors by the microbe cells rupture, which occurs in the area of the pressure gradients effect and the temperature pulsation.

Hydrodynamic cavitation is a more promising method. The results that testify to the disinfection effect of the hydrodynamic cavitation are presented in the paper.

The author [11] presented the possibility to apply hydrodynamic cavitation installation of static type. Similar results were obtained by the authors [12] while investigating the hydrodynamic cavitation effect on the *E.coli* microorganisms in cavitation installations of static and rotor types. The analyses of the results presented in the mentioned paper testified that the disinfection effectiveness, depending on the initial microbe concentration and technological parameters of treatment, were not studied enough. Besides, as to the disinfection mechanism and kinetics under the hydrodynamic cavitation, they are not reported enough in the literature.

The objective of our paper is to investigate the kinetic regularities of the *E.coli* microorganisms inactivation, to interpret the disinfection mechanism under cavitation and to study the complex effect of the cavitation and chemical oxides (hydrogen peroxide and silver ions in different combination) on *E.coli* microorganisms.

2. Experimental

Experimental investigation of disinfection, depending on the treatment regimes, microbe concentration and the definition of the disinfection mechanism, was carried out using the cavitation installation of dynamic type [13]. The design of this installation makes it possible to provide such regime parameters: rotation speed of the cavitation impeller $55< n <125$ s^{-1}, specific consuming energy $46.8 < \varepsilon <100$ W/dm^3, modified Reynolds number $3\cdot10^5 < Re_m < 6\cdot10^5$, cavitation number $3.2 < \sigma < 0.5$.

The investigations of inactivation of microorganisms of natural conglomerates were carried out in the hydrodynamic cavitation installation of static type [14]. The static installation is characterized by such regime parameters: liquid waste $9 < Q < 11.5$ m^3/h, rate of liquid flow in the gap $16.6 < v < 21.2$ m/s, specific consumed energy $28 < \varepsilon < 42$ W/dm^3, Reynolds number $6\cdot10^4 < Re < 8\cdot10^4$, cavitation number $2.6 < \sigma < 1.5$, cavitation stage $\lambda = 2.6$. Hybrid method of disinfection using chemical oxides was analysed in the installations of dynamic and static types to choose the most suitable method of treatment. 24-hour culture *E.coli*, grown on the meat-pepton broth (MPB), was the object of investigation. Bacteria suspension of 10^7 ind/sm^3 density was made of this 18-hour broth culture. Distilled water was used to prepare test solutions, in which *E.coli* bacteria were brought to the final concentration 10^4, 10^5 or 10^6 ind/cm^3, which equals the real pollution of the river water.

Antimicrobial effect of the hydrodynamic cavitation was studied by the *E.coli* bacteria survival. Probes selection was carried out at definite periods of time, after which planting of probes was carried out (or corresponding growing) in the Endo medium with further cultivation in the thermostat at the temperature of 310 K for 20–24 h. Bacteria survival was presented as the relation logarithm of the survived microorganisms number (N_t) to the initial number (N_0) – $\lg(N_t/N_0)$.

The rate of the microorganisms dying (K) was found according to the formula:

$$K = \frac{\lg(N_t / N_0}{t} \qquad (1)$$

where $\lg(N_t/N_0)$ – decimal logarithm of the relation of the survived cells to their initial number; τ – exposition time, s [1].

Experimental investigations of the microorganisms inactivation of the natural conglomerates were carried out in the static type cavitation installation. The treatment was carried out under previously created optimal operation regime of the installation, which are characterised by such parameters: specific consuming energy ε = 42 W/dm^3, Reynolds number $Re = 8\cdot10^4$, cavitation stage $\lambda = 2.6$.

To carry out the investigations of disinfection using chemical oxides under cavitation hydrogen peroxide or Ag(I) as $AgNO_3$ salt solution with the concentration of 20; 50 and 0.005; 0. 01 mg/dm^3, respectively were brought into the water suspension of *E.coli* bacteria. Natrium thiosulphate solution was used to neutralize the hydrogen peroxide, NaCl was used to neutralize the silver ions.

The effect of hybrid hydrodynamic and chemical cavitation was estimated according to the relation *T/E*, where *T* – portion of survived microorganisms, calculated theoretically; *E* – experimental data. Under theoretical calculation of a portion of the survived microorganisms, independent effect of each agent separately was taken into account [16]. According to the available classification, when $T/E < 1$ the antagonistic effect is observed, when $T/E = 1$ – additive effect, and when $T/E < 1$ – synergism effect of the disinfection agents.

3. Results and Discussion

3.1. Treatment Regimes and Microbe Concentration Effect on the *E.coli* Inactivation

In Figs.1 and 2 the kinetic curves of the *E.coli* microorganisms inactivation rate dependence in water are presented. The analysis of results testifies that the microorganisms dying rate depends both on the treatment regimes (Fig. 1) and the microbe concentration (Fig. 2).

As it is seen from Fig. 1, the increase of the cavitation impeller speed causes the increase of the microorganisms inactivation rate. Thus, during 14-min treatment under $Re_m = 3\cdot10^5$, the initial amount of *E.coli*

10^3 ind. /cm^3 decreased by 82 %, but under $Re_n = 6 \cdot 10^3$, 99 % of bacteria were inactivated. This is due to the fact that under cavitation stirring there appear cavities which collapse and form a great number of bubbles, the more intensive the stirring regime ($4 \cdot 10^5 < Re_m < 6 \cdot 10^5$) – the more developed the cavitation stage, which is characterized by the presence of the greater number of the cavitation bubbles of small sizes 0.8–1.2 mm in the investigated volume, which under the increase of the impeller rotation speed fuse into one cavitation field. Splashing of the vapour gas bubbles causes the impact waves, which affect the microbe cells fatally. For the investigated treatment regimes the Reynolds number values were: $Re_m = 2 \cdot 10^5$, $Re_m = 3 \cdot 10^5$, $Re_n = 4 \cdot 10^5$ and $Re_m = 6 \cdot 10^5$; *E.coli* microorganisms dying rate values were $2 \cdot 10^{-4}$; $1 \cdot 10^{-3}$; $1.6 \cdot 10^{-3}$ and $2.3 \cdot 10^{-3}$ s^{-1}, respectively.

In Fig. 2 the results of investigations of the kinetic dependencies of the *E.coli* microorganisms inactivation, depending on the microbes concentration, are demonstrated. For visual demonstration this process is presented as a logarithm $\lg(C/C_0)$ of relation of the number of microorganisms which survived in the definite treatment period (C) to the number of microorganisms in the initial water probe (C_0).

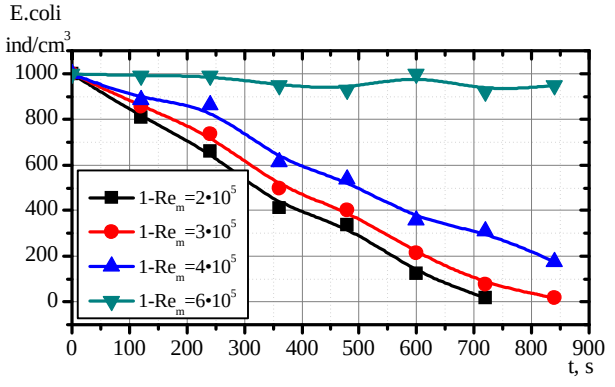


Fig. 1. Change of *E.coli* microorganisms concentration depending on time. $C_0 = 10^3$ *E.coli*/ml, $T = 288$ K

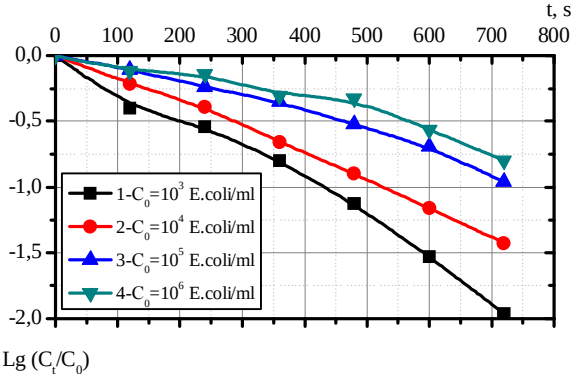


Fig. 2. Dependence of $\lg = C_t/C_0$ on t under different C_0. $Re_m = 6 \cdot 10^5$, $T = 288$ K

Curve 1 demonstrates the disinfection kinetics of *E.coli* microorganisms suspension with 10^6 ind./sm concentration, which is similar to that of sewages pollution. Under such purification during the experiment (12 min) only 15 % of *E.coli* microorganisms were disinfected. To achieve the proper level of disinfection (99.9 %) such microorganism suspension must be treated during 50–60 min (determined by the extrapolation method). When initial microbe concentration of the polluted water is less than 99.9 % the disinfection lasts for 20–25 min.

When the initial pollution is less than 10^3 ind./sm^3, 99.9 % disinfection effect is obtained in 10–12 min. These investigations were carried out under the similar energy characteristics of the experimental stand ($\varepsilon = 100$ W/dm^3) and under different microorganism concentration in the investigated volume. Efficiency of the energy used (12 ind./J) in all cases was the same.

Microorganisms dying rate constants under the microbe concentration of 10^6, 10^5, 10^4 and 10^3 ind./cm^3 were $1.1 \cdot 10^{-3}$, $1.3 \cdot 10^{-3}$ $1.8 \cdot 10^{-3}$ and $2.3 \cdot 10^{-3}$ s^{-1}, respectively. Thus, the highest disinfection rate is found under $Re_m = 6 \cdot 10^{-5}$, $\varepsilon = 100$ W/dm^3, $\sigma = 0.5$. That is why all further investigations were carried out under these treatment regimes.

3.2. Disinfection Mechanism

To find the disinfection mechanism investigations of the structural-morphological changes, which occur in the *E.coli* microbe cell under the hydrodynamic cavitation effects (Figs. 3 and 4) were carried out. In the testing probes intestinal bacillus cells have the form of short sticks with round edges of homogeneous optical density with clear shell outlines (Fig. 3).

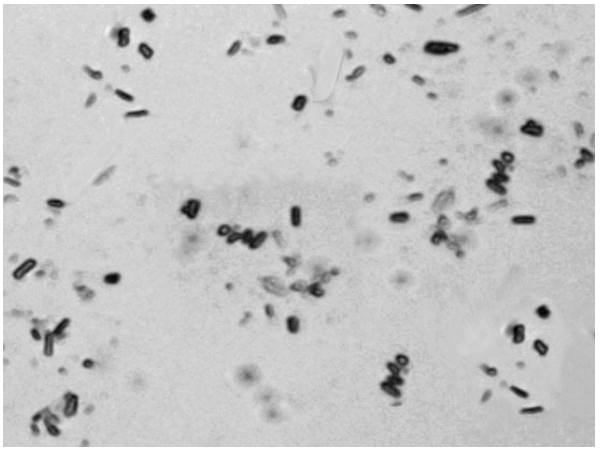


Fig. 3. *E.coli* culture in the probes of distilled water (testing). Magnification of 1650x. $C_0 = 10^3$ *E.coli*/ml, $T = 288$ K

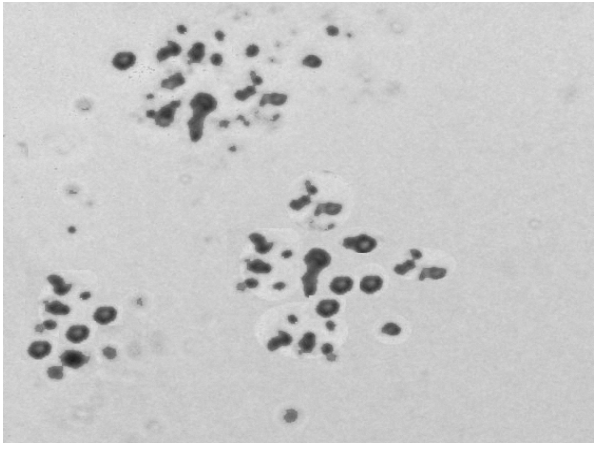


Fig. 4. *E.coli* culture after 10-min processing in cavitation installation. Magnification of 1650x. $C_0 = 10^3$ *E.coli*/ml, $Re_m = 6 \cdot 10^5$, $T = 288$ K

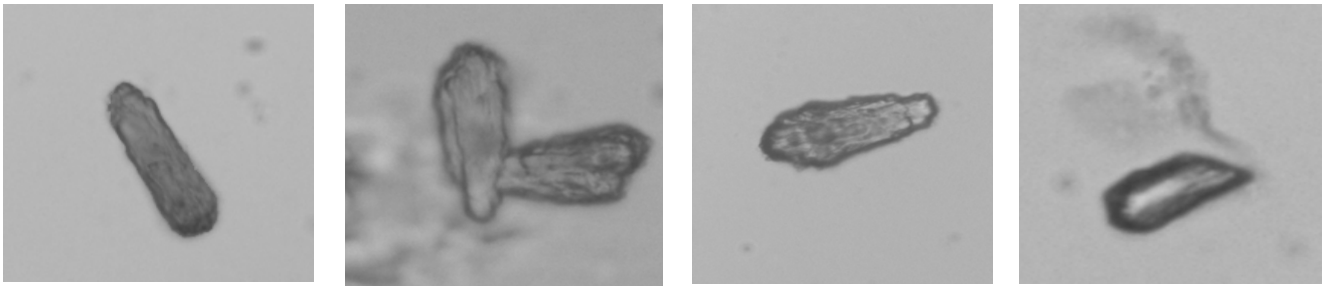
As it is seen from Fig. 1, the increase of the cavitation impeller speed causes the increase of the microorganisms inactivation rate. Thus, during 14-min treatment under $Re_m = 3 \cdot 10^5$, the initial amount of *E.coli* 10^3 ind. /cm^3 decreased by 82 %, but under $Re_n = 6 \cdot 10^3$, 99 % of bacteria were inactivated. This is due to the fact that under cavitation stirring there appear cavities which collapse and form a great number of bubbles, the more intensive the stirring regime ($4 \cdot 10^5 < Re_m < 6 \cdot 10^5$) – the more developed the cavitation stage, which is characterized by the presence of the greater number of the cavitation bubbles of small sizes 0.8–1.2 mm in the investigated volume, which under the increase of the impeller rotation speed fuse into one cavitation field. Splashing of the vapour gas bubbles causes the impact waves, which affect the microbe cells fatally. For the investigated treatment regimes the Reynolds number values were: $Re_m = 2 \cdot 10^5$, $Re_m = 3 \cdot 10^5$, $Re_n = 4 \cdot 10^5$ and $Re_m = 6 \cdot 10^5$; *E.coli* microorganisms dying rate values were $2 \cdot 10^{-4}$; $1 \cdot 10^{-3}$; $1.6 \cdot 10^{-3}$ and $2.3 \cdot 10^{-3}$ s^{-1}, respectively.

In Fig. 2 the results of investigations of the kinetic dependencies of the *E.coli* microorganisms inactivation, depending on the microbes concentration, are demonstrated. For visual demonstration this process is presented as a logarithm $\lg(C/C_0)$ of relation of the number of microorganisms which survived in the definite treatment period (C) to the number of microorganisms in the initial water probe (C_0).

Formation of the chemically active compounds, OH hydroxyl radicals and hydrogen peroxide H_2O_2 in water during its cavitation treatment is testified by the investigation results [17]. Hydroxyl radicals during their effect on the SH-groups, hystide and other aminoacid protein radicals cause their denaturation and inactivate the ferments. In the nuclein acids OH radicals rupture the hydrogen bonds between the nucleotides and break DNK and RNK chains and cause the cells dying. Besides, hydroxide radicals penetrating into the cell membrane lipide layer, initiate the chain lipide oxidation reactions, which cause the membranes rupture and loss of their functions, which results in the cell dying. Disinfection effect of the hydrogen peroxide is reached due to its high oxidation ability, which results in decreasing of the cell membrane surface tension and loss of the protein synthesis [2]. Ozone concentrations are negligible (< 0.05 mg/l), that is why it can not affect the process sufficiently [17].

At 2000 time increase (Fig. 5), the change of the *E.coli* cell structure is testified as the result of such factors as tension gradients, local temperatures, *etc*. (Fig. 5b, c, d). Cytoplasm membrane is disintegrated, its degeneration occurs (probably due to the ferment processes stop). As a result, the dispersion of the cytoplasm colloid structure is ruined and causes the appearance of ions and low-molecular cytoplasm components in the environment (Fig. 5d).

Based on the structural-morphological investigation results, physical model of the hydrodynamic cavitation disinfection was proposed. According to this model disinfection effect is caused by the simultaneous effect of the shock waves, tension gradients, high local temperatures, cumulative streams, and OH and H_2O_2 chemical compounds.



a) b) c) d)

Fig. 5. *E coli* culture in the probes of distilled water (testing) (a) and after 10-min treatment in cavitation installation (a, b, d). Magnification of 20000x

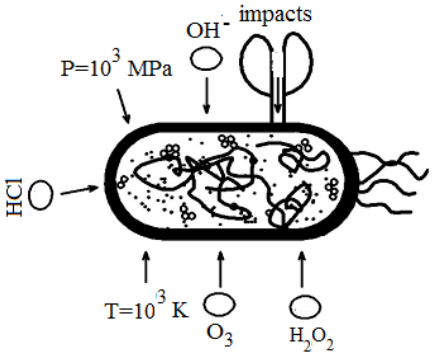


Fig. 6. Physical model of cavitation effect on the microbes

Thus, the number of inactivated microorganisms can be found according to the equation:

$$C = C_1 + C_2 \quad (1)$$

where C – total number of the inactivated microorganisms caused by the mechanical and chemical effects of the cavitation field phenomena, ind./cm^3; C_1 and C_2 – number of microorganisms inactivated due to separate mechanical effects and chemical factor, respectively, ind./cm^3;

Initial conditions of the process $\tau_0 = 0$; $C_0 = 0$.

At the same time, concentration of the inactivated microorganisms C is in proportion to the specific energy:

$$C = pe \quad (2)$$

where ε – specific energy, W/cm^3; p – proportional factor.

The microorganisms inactivation rate can be described by the equation:

$$\frac{dC}{dt} = k_1 e \quad (3)$$

Then the *E.coli* inactivation process can be presented by the system of the kinetic equations:

$$\begin{cases} \dfrac{dC}{dt} = \dfrac{dC_1}{dt} + \dfrac{dC_2}{dt} \\ \dfrac{dC_1}{dt} = k_1 e - k_2 C_1 \\ \dfrac{dC_{21}}{dt} = k_1 e - k_3 C_2^2 \end{cases} \quad (4)$$

where k_1 – microorganisms inactivation rate constant caused by all cavitation field effects, ind./W·s; k_2 – microorganisms inactivation rate constant caused by the mechanical effects of the cavitation field, s^{-1}; k_3 – microorganisms inactivation rate constant caused by the chemically active compounds effect, cm^3/ind.·s.

Constants k_1, k_2 and k_3 were obtained by the computer processing of the experimental data (Fig. 7).

Having solved the system of differential equations (4), analytical dependencies for finding C, C_1 and C_2 were obtained as:

$$C_1 = -\frac{k_1}{k_2} \cdot e \cdot (ae^{-k_2 t} - 1) \quad (5)$$

where a – integration constant found from the initial conditions, $a = 1$.

$$C_2 = \frac{\sqrt{k_1 \cdot e} \cdot th(\sqrt{k_1 \cdot k_3 \cdot e} \cdot (t + b))}{\sqrt{k_3}} \quad (6)$$

where b – integration constant found from the initial conditions, $b = 0$;

$$C = \frac{\sqrt{k_1 \cdot e} \cdot th(\sqrt{k_1 \cdot k_3 \cdot e} \cdot (t + b))}{\sqrt{k_3}} - \frac{k_1}{k_2} \cdot e \cdot (ae^{-k_2 t} - 1) \quad (7)$$

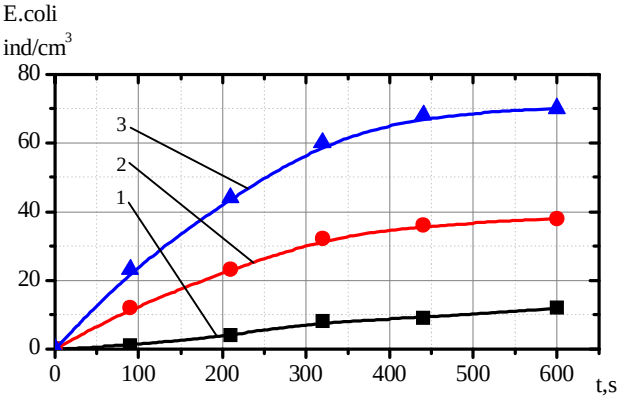


Fig. 7. Change of *E.coli* inactivated microorganisms concentration depending on time: under the effect of hydroxyl radicals (1); under mechanical effects (2) and under the effect of hydrogen peroxide (1.32 mg/l) (3)

To extend the application range of Eqs. (5), (6) and (7), the values of constants k_1, k_2 and k_3 within the consumed energy amount $0.04 < \varepsilon < 0.1$ W/cm^3 were found. The results are presented in Table 1.

Table 1

Reaction constant values for different cavitation treatment regimes

Constants	Consumed energy, W/sm^3				
	0.04	0.05	0.06	0.08	0.1
k_1, ind./W·s	5.5	4.05	3.3	2.9	2.4
k_2, s^{-1}	$6.25 \cdot 10^{-3}$	$4.63 \cdot 10^{-3}$	$2.92 \cdot 10^{-3}$	$2.62 \cdot 10^{-3}$	$2.17 \cdot 10^{-3}$
k_3, cm^3/ind.·s	$1.307 \cdot 10^{-3}$	$1.04 \cdot 10^{-3}$	$0.644 \cdot 10^{-3}$	$0.42 \cdot 10^{-3}$	$0.27 \cdot 10^{-3}$

Comparison of the experimental data with those of mathematic calculations according to Eq. (7) is presented in Fig. 8. Comparison of the experimental data with theoretical ones, obtained according to Eq. (7), demonstrated that the error does not exceed 8.3 %, that is why this equation can be used for prediction of the disinfection process.

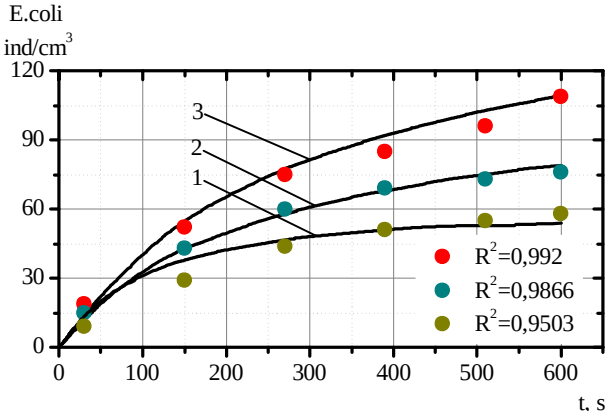


Fig. 8. Change of the *E.coli* inactivated microorganisms concentration under the hydrodynamic cavitation field effect in time (curve – the result of mathematic calculations, dots – experimental data): ε = 0.1 W/cm^3 (1); ε = 0.06 W/cm^3 (2) and ε = 0.04 W/cm^3 (3)

3.3. Inactivation of the Natural Conglomerate Microorganisms

Sanitary indices microorganisms, which are treated in water as the factors of fecal pollution, are TBGB and enterococci. Pollutions from the mucous membrane of the windpipe of a man and some other warm-blooded animals are staphylococci [18]. As to TBGB, similar to the previous investigations *Escherichia coli* monoculture was used, *Streptococcus faecalis* was chosen from the enterococci group and *Streptococcus aureus* as the representative of the staphylococci respectively. The treatment of the microorganism suspension was carried out in the static type experimental installation. Investigation results are presented in Fig. 9.

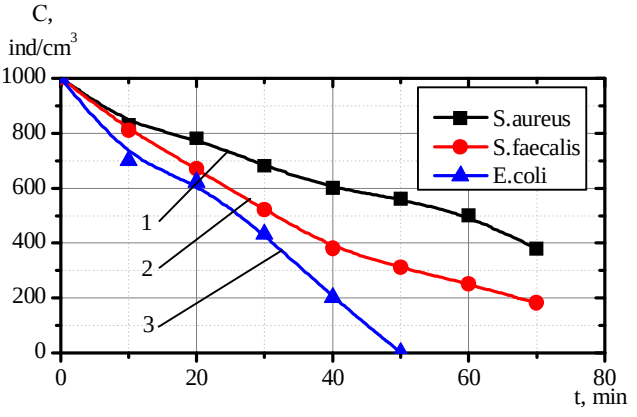


Fig. 9. Water contaminated with monocultures of *S.aureus* (1); *S.faecalis* (2) and *E.coli* (3). Re = 8·10^4, C_0 = 10^3 CFU/ml; T = 288 K

As it is seen from the graph, staphylococci possess the greatest resistance to the hydrodynamic cavitation effect. Enterococci possess less survival strength and the most affected among the studied ones are bacteria of the intestine bacillus. To decrease the concentration of *S.aureus* microorganisms (*curve* 1) from 10^3 to 0 ind./cm^3, the suspension must be treated for 2 h. To obtain 99.9 % disinfection effect with regard to *S.faecalis* (*curve* 2) the test organisms suspension must be treated in the hydrodynamic cavitation static type installation for not less than 90 min. Such exposition time in practical conditions is highly energy consuming. That is why, to accelerate the disinfection it is reasonable to simultaneously add the chemical oxides [15].

To model the disinfection process of well water and to define the optimal parameters of treatment natural bacteria association was used as the investigation object. In Fig. 10 the disinfection of the natural well water taken in the "Topilche" Park in the hydrodynamic static type cavitation installation without chemical oxides, is shown. According to the demands as to the shortened epidemic safety control indices list, GMN and TBGB factors were found [19].

In Fig. 10 the *curve* 1 demonstrates the dying kinetics of the intestine bacillus group bacteria (dimension in ind./dm^3), the *curve* 2 demonstrates the inactivation process of the total microbe number (ind./dm^3). According to the standards adopted in Ukraine "Sanitary maintenance standards of bore wells and well water catchments, used for the decentralized utility water supply" No 1226–75, the water probes before treatment, according to the analyzed data (GMN – 10 NEU/cm^3, TBGB factor – 23), do not meet the standards as to the amount of TBGB. After 10-min treatment in the cavitation installation the total microbe number is 3 NEU/cm^3 and TBGB factor – 9.These data meet the standards of bore well water. Microbiological factor standards for the drinking water safety are more strict (TBGB factor must not exceed 3), which is obtained after 13min treatment. As it is seen from Fig. 10, 99.9 % disinfection of water is obtained in 14–16min after treatment in the hydrodynamic cavitation installation.

Disinfection effect of the hydrodynamic cavitation in the sufficiently contaminated water was studied. The investigations were carried out in the cavitation static type installation in the natural water of the Ternopil lake. Sanitary microbiological control was carried out according to the standards adopted in Ukraine "Protection of surface water from pollution" by the lacto-positive intestine bacilli index, *E.coli* intestine bacillus factor (LIB) and enterococci factor. The results are presented in Fig. 11.

As it is seen from Fig. 11 during 30-min treatment inactivation of the lacto-positive intestine bacilli was the most efficient (LIB factor after treatment – 200) and the

least efficient (only 50 %) was the enterobacteria factor (enterococci factor after treatment – 250). This testifies the results obtained during the disinfection of water contaminated by the monoculture microorganisms (Fig. 9), where it was found that the Streptococcus faecalis microorganism inactivation rate is lower than that of *E.coli* inactivation. During 30 min treatment in the hydrodynamic cavitation installation 100 % disinfection of water from the surface reservoirs was not obtained. Hence, cavitation effect on microorganisms does not provide the desired level of disinfection. That is why the hybrid method of treatment using chemical oxides is the alternative method of treatment.

3.4. Hybrid Disinfection Method

In Fig.12 disinfection effect of the hydrodynamic cavitation and the anti-microbe effect of the 20 and 50 mg/dm^{3}concentration hydrogen peroxide in the conditions of turbulent stirring and cavitation scheme, are presented. Inactivation kinetics under treatment of the microorganism suspension in the dynamic type installation is presented in Fig. 12a and in the static type installation – in Fig. 12b.

The presented data testify that adding of hydrogen peroxide in the cavitation installation increases the anti-microbe effect. Thus, *E.coli* inactivation rate constant in the dynamic cavitation installation at $Re_m = 6 \cdot 10^5$ equals 0.003 s^{-1}; when H_2O_2 of 20 mg/dm^3 concentration is added it increases up to 0.006 s^{-1}; whereas adding of 50 mg/dm^3 of hydrogen peroxide increases the constant almost by order – K = 0.038 s^{-1}. Similar regularity is demonstrated under the disinfection in the static installation (Fig. 11b).

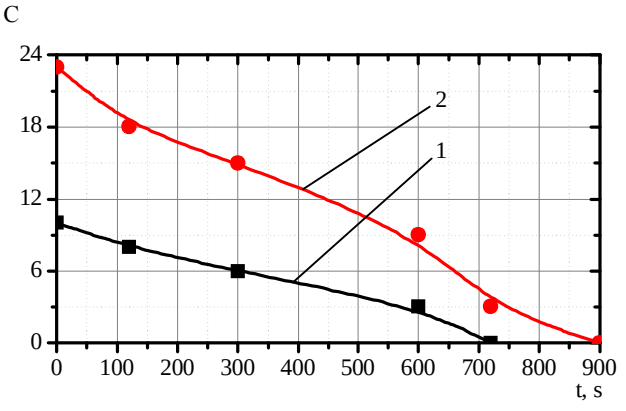


Fig. 10. Change of sanitary standards with time, water from the "Topilche" Park well: TBGB, ind./l (1) and total microbial count, ind./ml (2)

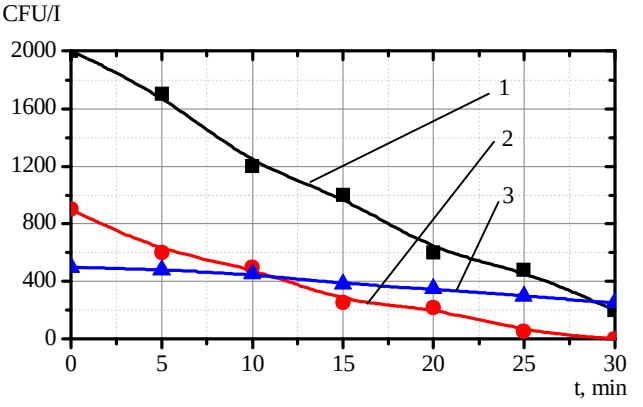
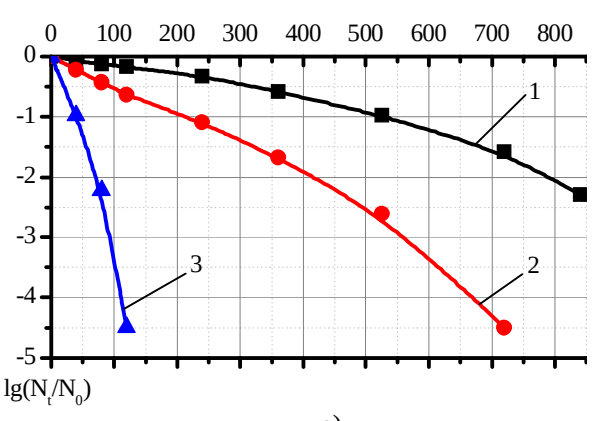
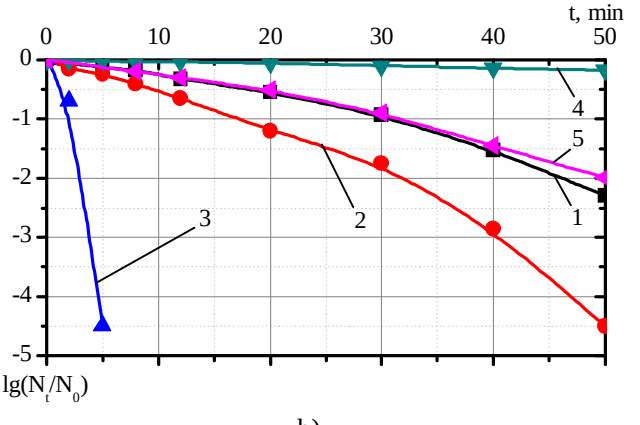


Fig. 11. Change of sanitary standards with time, water from the Ternopil lake: total coliforms (1); faecal coliforms (2) and faecal enterococci (3)



a)



b)

Fig. 12. Logarithmic dependence of *E.coli* inactivation in the cavitation installations of dynamic (a) and static (b) type: H_2O_2 of 20 mg/dm^3 concentration (1); H_2O_2 of 50 mg/dm^3 (2); treatment in the cavitation installation (3); 20 mg/dm^3 hydrogen peroxide effect in cavitation conditions (4) and 50 mg/dm^3 H_2O_2 effect under cavitation (5)

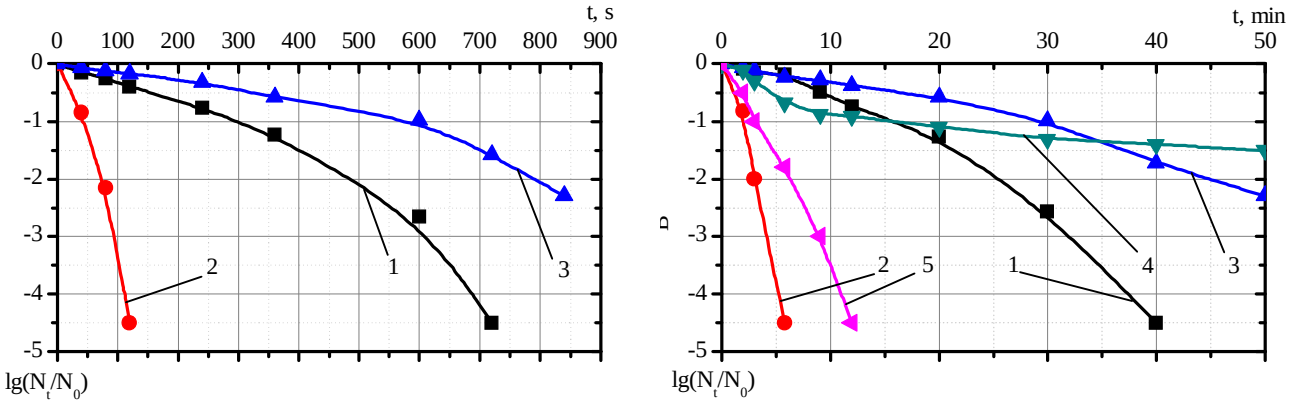


Fig. 13. Logarithmic dependence of *E.coli* inactivation in the cavitation installation of dynamic (a) and static (b) type: 0.005 mg/dm^3 Ag(I) effect (1); hydrodynamic cavitation effects (2); 0.005 mg/dm^3 Ag(I) effect under cavitation (3); 0.01 mg/dm^3 Ag(I) effect (4) and 0.01 mg/dm^3 Ag(I) effect under cavitation

Similar investigations were carried out using the silver ions. The results are presented in Fig. 13. Comparison of the experimental data testifies that under water disinfection with Ag(I) ions in the cavitation conditions the anti-microbe result increases and the "tag" effects on the microorganisms dying curve under the effect of 0.005 mg/dm^{3}concentration Ag(I) disappear (Fig. 13b, *curve* 1).

The mechanism of improvement of the disinfection effect using chemical oxides under cavitation stirring can be caused by:

1) the effect of chemically active compounds, which are formed inside the cavitation bubbles: hydrogen peroxide H_2O_2; hydroxyl OH and ozone O_3 radicals;

2) the formation of a great number of 10^{-6} m size vapor-gas bubbles, which splash periodically and create unsteady to obtain the sufficient condition, which causes rapid penetration of disinfection chemicals inside the cell, and results in the affection of the cell viability;

3) the change of pH [17] towards alkaline (hydrogen peroxide bactericidal effect is improved);

4) the formation of OH radical as the result of the Fenton effect (under the cavitation hydrogen peroxide transition in water from the vapor-gas phase [17], that is why, when Ag(I) ions are available, the Fenton reaction occurs.

For practical application of the proposed technique and complex estimation of the efficiency and intensity of the investigated treatment techniques it is necessary to find the proper time needed disinfection effect. The time needed for 99 % microorganism inactivation ($\lg N_t/N_0$ = -4.5) was found according to the *E.coli* dying kinetic curves in water under the effects of hydrodynamic cavitation, hydrogen peroxide, silver, and their combinations (Figs.12 and 13). The results of these calculations are presented in Table 2.

The analysis of data presented in Table 2 testifies that adding of $AgNO_3$ or hydrogen peroxide results in 9–45 time decrease of time of the suspension treatment in the cavitation installation. Comparison of the microorganism inactivation rate in the dynamic and static types of installation testifies that adding of silver in the installation of dynamic type makes it possible to accelerate the process 9–10 times, while in the static type installation – 2–3 time acceleration is obtained. Adding of hydrogen peroxide in the cavitation installation of dynamic type results in 25–45 time shortening of this process (depending on the reagent concentration) and in the static type installation – in 10–11 time shortening. Thus, in both cases the highest intensity of the process is obtained in the installation of dynamic type, which is caused by the greater vapor-gas phase volume, which provides the efficiency of the cavitation effect.

From the practical point of view, the manner of interrelation of the investigated disinfection chemicals (mutual or synergism effect) is of great importance too. That is why the values of *T/E* under different kinds of investigations were calculated. The results of calculations for the cavitation installation of dynamic type are presented in Table 3 and for the static type installation – in Table 4.

The data form Tables 2 and 3 testify the change of almost additive character of the disinfecting chemicals ($AgNO_3$ and N_2O_2) and hydrodynamic cavitation effects interrelation under their small concentrations (0.005 and 20 mg/dm^3, respectively) and short exposition to the synergic one; the value of the synergic effect being greater with the increase of the exposure time and the increase of the hydrogen peroxide concentration and adding of the Ag(I) ions. Maximum *T/E* value is found under *E.coli* disinfection by 50 mg/dm^3 H_2O_2 concentration in the condition of the cavitation stirring in the dynamic type installation during 120 s contact and equals 246.

Table 2

Calculation results of the time (min) necessary for 99 % *E.coli* disinfection in water under the effect of reagent, hydrodynamic cavitation and their hybrids

Method of disinfection	Concentration of reagent, mg/dm^3		
	0	0.005	0.01
Ag(I) (turbulent regime)	–	70	10
Ag(I) + cavitation regime (static installation)	55	35	4
Ag(I) + cavitation regime (dynamic installation)	14	10	2
	0	20	50
H_2O_2 (turbulent regime)	–	450	65
H_2O_2 + cavitation regime (static installation)	55	48	5
H_2O_2 + cavitation regime (dynamic installation)	14	11	2

Table 3

Hybrid effect (*T/E*) of chemical reagents and cavitation on *E.coli* (dynamic installation)

C, mg/dm^3		Treatment time, s					
Ag(I)	H_2O_2	40	80	120	240	360	600
0.005	-	2.43	2.64	3.07	4.82	9.6	50.8
0.01	-	11.43	193	not found	not found	not found	not found
-	20	3.05	4.57	6.97	16.7	28.7	87.4
-	50	15	81.5	246	not found	not found	not found

Table 4

Hybrid effect (*T/E*) of chemical reagents and cavitation on *E.coli* (static installation)

C, mg/dm^3		Treatment time, min						
Ag(I)	H_2O_2	2	5	8	12	20	30	40
0.005	-	1.73	2.06	2.92	3.48	7.06	35.7	not found
0.01	-	8.6	182	not found	not found	not found	not found	not found
-	20	2.5	2.78	3.77	5.53	6.05	28.3	78.75
-	50	8.25	214.3	not found	not found	not found	not found	not found

From the energy consumption point of view application of installations of both dynamic and static type [14] is reasonable. At the same time, under hybrid application of the cavitation effects and chemical oxides the efficiency of energy consumption is higher in the static type installation due to adding of chemical reagents directly into the vapor-gas cavity [14].

4. Conclusions

The mechanism and kinetic regularities of the inactivation cavitation effects on microorganisms were investigated. Based on the structural-morphological investigation of *E.coli* microorganisms mechanism of hydrodynamic cavitation disinfection effect was found. Antibacterial effect is obtained due to the physical-chemical effects of cavitation field, under the influence of which mechanical rupture of cells occurs as well as chemical disinfection under the influence of hydroxyl radicals and hydrogen peroxide. Regularities of the *E.coli* dying, depending on the treatment regimes and microbe population have been studied. The results testified that under the turbulent regime inactivation of microorganisms does not occur. Under cavitation regime bacterium dying rate grows as Reinold's Re_m increases and microbial contamination decreases. While disinfecting by the chemical oxides (H_2O_2 and $AgNO_3$) under cavitation stirring synergic action occurs, which allows to decrease the disinfection time and the concentration of reagents by 50–70 %. Comparison of the operation intensity and effectiveness of the dynamic and static types of installations has shown that the disinfection process in the dynamic type installations is 3 times more effective while the efficiency of energy consumption is 2 times higher in the static type installations.

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МЕХАНІЗМ ТА КІНЕТИЧНІ ЗАКОНОМІРНОСТІ ІНАКТИВУЮЧОЇ ДІЇ КАВІТАЦІЇ НА МІКРООРГАНІЗМИ

Анотація. *Вивчено знезаражуючу дію фізико-хімічних ефектів, що супроводжують гідродинамічну кавітацію на санітарно-показникові мікроорганізми у воді. Встановлено, що кінетика знезараження залежить від характеристик кавітаційного поля і мікробного навантаження. На основі структурно-морфологічних досліджень бактерій E.coli, встановлено, що антимікробний ефект досягається внаслідок механічного руйнування клітин і хімічного знезараження під впливом радикалів гідроксилу і пероксиду водню. Запропоновано математичну модель, яка дає можливість прогнозувати результат знезараження в умовах гідродинамічної кавітації. Досліджено дію хімічних реагентів на мікроорганізми E.coli, в умовах гідродинамічної кавітації. Встановлено, що введення $AgNO_3$ або пероксиду водню в кавітаційні пристрої дає можливість скоротити тривалість знезараження та зменшення концентрацій хімічних окисників на 50–70 %, що пояснюється синергічним ефектом.*

Ключові слова: *гідродинамічна кавітація, знезараження, мікроорганізми, кінетика.*