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DETERMINATION OF THE RATE CONSTANT OF MICROORGANISMS DESTRUCTION AFTER ULTRASOUND WATER TREATMENT AND DIFFERENT GASES ACTION

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Abstract. The change of microorganisms number (rod-like spore-containing *Bacillus cereus* bacteria type) for the range of $10^2 \div 10^6$ CFU in 1 cm^3 from the duration of simultaneous action of ultrasound (US) cavitation and the nature of different gas (carbon dioxide, oxygen, argon) is presented. The graphical dependences of the effective rate constant values of microorganisms destruction (k_d) on its initial number per unit volume of water at different modes of its treatment are shown. The destruction degrees of bacterial cells in the process of water purification are calculated. It was investigated that the value of k_d does not depend on the initial number of cells in water, but depends on the nature of the bubbled gas through the reaction aqueous medium: $k_{d(Ar/US)} > k_{d(O2/US)} > k_{d(CO2/US)}$.

Keywords: ultrasound action, cavitation process, microorganisms destruction, oxygen, carbon dioxide, argon.

1. Introduction

Cavitation disinfection of water, which consists of the processes of microorganisms destruction by ultrasonic radiation, is explained by cavitation processes, which include the formation, growth, and collapse in the liquid of pulsating cavitation bubbles filled with gas, steam, or their mixture.[1,2] The pressure that occurs inside these cavities during their formation is very small when compared to the pressure in the liquid itself. As a result, the liquid and the gases dissolved in it are sent to the center of the bubble. Under the action of the ambient pressure of the liquid, the diameter of the bubble decreases sharply, which leads to its collapse. Around the points of the collapse of the caverns, there is the complete destruction of microorganisms present in the liquid, as the processes of destruction of micro-objects are caused by the energy released as a result of the collapse of bubbles.

The course of chemical reactions that occur under the action of ultrasonic radiation is significantly influenced by bubbled gaseous substances, as gas bubbles play the role of cavitation nuclei in the reaction medium.[3-5] Dissolved gas, on the one hand, provides an excess of nuclei for the formation of bubbles in the cavitation zones, and on the other hand – increases the pressure in the bubbles and reduces the rate of their collapse.[1]

Studies show[6-9] that the presence of gases affects the rate of microorganisms destruction in water and determines the effectiveness of water disinfection under cavitation conditions. The intensifying effect of gases in the processes of cavitation water disinfection[7] was confirmed and the synergistic effect of the combined action of gas and ultrasound cavitation was revealed: $k_{d(gas/US)} > k_{d(gas)} + k_{d(US)}$. The dependence of the microorganisms destruction efficiency on their variety in water was studied in our previous work,[8] which shows the correlation between the effective rate constants of different microorganisms destruction (k_d) and their cell size. It was found that $k_{d(yeast\ cells)} >> k_{d(bacterial\ cells)}$.

After exposure of air to a suspension containing *Saccharomyces cerevisiae* at a concentration of $3 \cdot 10^5$ cells/cm^3 after 10 minutes of treatment with a piezoelectric generator (800 kHz, 7 W/cm^2), the cells were destroyed by 90 %, while in a hydrogen atmosphere yeast cells reactivation was observed, but they were destroyed in an atmosphere of argon, oxygen and air.[6] The effect of carbon dioxide on the microorganism viability was studied in our previous work,[10] where the effect of gas pressure in the microbubble as the most probable cause of cell death was investigated. The effect of low-intensity ultrasound (with different frequency, treatment duration and power) on the yeast *Saccharomyces cerevisiae* in different phases of cell growth is described[11] and it is shown that the biomass of *Saccharomyces cerevisiae* increases by 127.03 % under optimal ultrasonic conditions (power 140 W/L and ultrasound duration 1 hour). The inactivation of *Saccharomyces cerevisiae* cells by ultrasonic irradiation with an initial cell number from 10^2 to 10^5 mL^{-1}, in which the inactivation rate constants varied from

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0.023 to $6.4 \cdot 10^{-3}$ s^{-1}, was studied. 90 % of yeast cells inactivation was achieved by ultrasonic irradiation at a frequency of 26.6 kHz for 60 min.[12]

As we see, many works are devoted to the study of the ultrasound effect on the yeast cells activity. However, few experimental works on the destruction of the bacterial cells in the ultrasound field have been found, which do not explain the effect of the bacteria amount on the cavitation treatment efficiency of cells in water. Therefore, the present work is directed on the study of the effect of bacterial cells initial quantity in the water system on changing the effective rate constant value of their destruction in different gas atmospheres.

2. Experimental

The micro-objects selection for experiments is directly related to the processes of microorganisms identification in different water sources. Qualitative and quantitative composition of microorganisms was determined in natural and wastewater of Lviv region. For this purpose, a series of microscopic studies were performed, namely: microscopy of preparations within *vivo* staining, "crushed drop" preparations, stained preparations of fixed cells, stained cells with Lugol's solution, stained cells according to Gram.[13] We also studied the cultural characteristics of microorganisms and determined microorganisms response to oxygen (physiological feature). Microscopic examinations of natural and wastewater samples revealed the microorganisms types present in these waters. The dominant type of bacteria served to select test microorganisms as aquatic micro-objects.

Oxygen, carbon dioxide and argon were used to bubble the aquatic environment. The gas was bubbled through water throughout the cavitation process at a rate of 0.2 cm^3/s. The gas consumption was 0.7 dm^3/h.

For the cavitation source, an ultrasonic generator UZDN-2T with a frequency of 22 kHz and a power of 35 W was used. The experimental conditions were as follows: T = 298 ± 1 K, P = 0.1 MPa, the total duration of the water treatment process was 2 hours.

Deaerated distilled water was used to create the microbial water by boiling it in an open container to remove dissolved gases, followed by cooling without air. A pure culture of the studied microorganisms was added to the cooled water by a microbiological loop. The total microbial load in the model waters ranged within four orders of magnitude, namely: 10^2–10^6 cells per unit volume of water. The number of cells in water was determined by the number of colonies grown on a nutrient medium, based on the fact that one colony grew from one cell.[13]

The nutrient medium for the growth of bacterial colonies was meat and peptone agar (MPA), which was previously tested for sterility without a water sample, *i.e.*, to determine the presence or absence of microorganisms colonies in the nutrient medium. The composition of MPA is as follows: meat water (1 dm^3), peptone (10 g), agar (15 g).

The prepared sample of test water was poured into a glass reactor with a capacity of 75 cm^3, which was constantly cooled by running water to maintain a constant temperature in the reaction medium (T = 298 ± 1 K). The magnetostrictive emitter, which transmitted ultrasonic vibrations, was immersed in the volume of the tested water sample. Simultaneously with the inclusion of the ultrasonic generator the supply of one of the studied gases was provided. Every 30 minutes of the process, water samples were taken for analysis.

The general number of microorganisms (NM) in 1 cm^3 of water was determined by the following steps:[13]

– preparation of dilutions;

– sowing on a solid nutrient medium into the Petri dishes;

– counting of colonies on the nutrient medium.

The step of seeding the water sample was that the melted MPA with a volume of 12–15 cm^3 and cooled to a temperature of 318–321 K was poured into a sterile Petri dish, which was previously poured into the test water with a volume of 1 cm^3. Next, these dishes were placed in a dry air thermostat at 310 K for 48 hours. Each water sample was seeded in three parallel Petri dishes by the depth method described by Slyusarenko.[13] The sequence of counting colonies grown on medium in Petri dishes is described in detail elsewhere.[14]

3. Results and Discussion

The results of microorganisms identification in different water sources (natural and waste) are presented in Table 1, where among the bacteria we observe the dominance of sporogenic rod-shaped bacteria of *Bacillus cereus* type, compared with spherical ones. Quantitative results of counting the detected microorganisms are expressed as a percentage. That is why the combined effect of ultrasonic cavitation and gas was studied on these rod-shaped bacteria, in particular on spore forms, which, in contrast to vegetative cells, are more resistant to external factors.

Water samples from open reservoirs were taken during the summer period (June-July). Samples of industrial wastewater were taken from their constant flow. For each water body, five samples were taken, followed by averaging the obtained cell counts per unit volume of water. It is determined that the initial microbial load in the studied natural waters fluctuated within 820÷2600 CFU/cm^3, and in industrial wastewater – 38600÷110000 CFU/cm^3.

Table 1. Identified microorganisms in water from different sources depending on the type and shape of cells

The source of the studied water	Microorganisms types			
	Bacteria		Yeast	Algae
	Spherical bacteria	Rod-shaped bacteria		
Natural water No1 (Lviv region)	*Sarcina* (27 %)	*Bacterium* (16 %), *Pseudomonas* (22 %), *Bacillus** (35 %)	–	–
Natural water No2 (Lviv region)	*Staphylococcus* (34 %)	*Pseudomonas* (26 %), *Bacillus** (40 %)	–	–
Natural water No3 (Lviv region)	*Sarcina* (9 %)	*Bacterium* (15 %), *Bacillus* (21 %), *Pseudomonas** (55 %)	–	–
Natural water No4 (Lviv region)	–	*Pseudomonas* (24 %), *Bacterium* (32 %), *Bacillus** (44 %)	–	*Oscillatoria* (99 %)
Natural water No5 (Lviv)	*Micrococcus* (18 %), *Streptococcus* (8 %), *Sarcina* (13 %)	*Bacterium** (29 %), *Bacillus** (32 %)	–	–
Wastewater No1 (brewery, Lviv)	Micrococcus (11 %), Sarcina (25 %)	*Bacterium* (11 %), *Pseudomonas* (18 %), *Bacillus** (35 %)	*Saccharomyces* (99 %)	–
Wastewater No2 (pharmaceutical plant, Lviv)	*Micrococcus* (10 %), *Streptococcus* (15 %), *Diplococcus* (19 %), *Sarcina* (21 %)	*Bacterium* (4 %), *Bacillus** (31 %)	–	–

Note: * in the dominant amount among bacteria

Having established the type of dominant microflora, further studies were aimed at studying the joint effect of ultrasound cavitation and gases on the process of water purification from microorganisms of the same types. The working NM_0 in the microbial waters created by us were $8{\cdot}10^2$; $2{\cdot}10^4$; $7{\cdot}10^5$; $1{,}5{\cdot}10^6$ and $3{\cdot}10^6$ CFU/cm^3, thus approaching the actual level of microbiological contamination of both natural and wastewater, which we previously found during the identification of aquatic micro-objects.

However, initially, the experiments were performed in the studied microbial water without the action of any factor, *i.e.*, without the influence of ultrasonic radiation and without bubbling gases. That is, the survival of bacteria was studied only in distilled deaerated water. To do this, a sample of water (1 cm^3) was taken from the microbial water with a microbiological loop every 10 minutes to count the number of cells. The total duration of such selections was two hours. The result of this study showed the invariance of the value of the NM, which indicates the lack of influence of the aquatic environment created by us on the activity of microorganisms during the study duration of the experiment.

The nature of the water disinfection process is shown in Fig. 1 as a change in the values of the NM from the duration of the water treatment regime during Ar/US and O_2/US action. That is, to compare the efficiency of water disinfection from the nature of bubbling gas, the study was carried out in the presence of argon as the most efficient gas under cavitation conditions[9] and oxidizing gas - oxygen capable of generating hydroperoxide radicals in the reaction medium under cavitation conditions,[15] thereby affecting the effectiveness of water disinfection. The values of the effective rate constant of the destruction of the bacterial cells in an argon atmosphere are summarized in Table 2, and for the oxygen atmosphere – in Table 3.

The diagrams (Fig. 1 a-e) describe the decrease of the NM values in time for all studied concentrations of cells in water. After a two-hour process, the number of bacillary cells under conditions of Ar/US at the initial: $2{\cdot}10^4$; $7{\cdot}10^5$; $1.5{\cdot}10^6$ and $3{\cdot}10^6$ CFU/cm^3 decreased by three orders of magnitude (Fig. 1 b-e), while under the action of O_2/US a similar effect was achieved at $7{\cdot}10^5$ and $1.5{\cdot}10^6$ CFU/cm^3 (Fig. 1 c-d), because at $2{\cdot}10^4$ and $3{\cdot}10^6$ CFU/cm^3 the number of cells decreased by only two orders of magnitude (Fig. 1 b and e).

According to Table 2, with increasing NM_0 we observe an increase in the destruction degree of bacteria (D_d). This is obviously due to the fact that with the increase in the number of microorganisms per unit volume of water, the probability of their entry into the zone of instantaneous formation of cavitation bubbles in the

ultrasonic field increases. However, the value of D_d increases only to a certain level of microbial load, at which the maximum possible degree of water disinfection is achieved. Thus, after Ar/US-action, the value of D_d = = 99.9 % was calculated at microbial load in the range of $7 \cdot 10^5 \div 1.5 \cdot 10^6$ CFU/cm^3, and after O_2/US-action – only at $1.5 \cdot 10^6$ CFU/cm^3. With a further increase in NM_0, the value of D_d after Ar/US action is 99.8 %, while after O_2/US action – 99.4 %. This indicates that the combined action of argon and ultrasonic cavitation allows to achieve higher degrees of water disinfection and keep it high even at microbial load $\geq 10^6$ CFU/cm^3, compared with the action of oxygen in similar experimental conditions, because in an oxygen atmosphere at NM_0 = = $3 \cdot 10^6$ CFU/cm^3 the destruction degree of bacteria begins to decrease (Table 2).

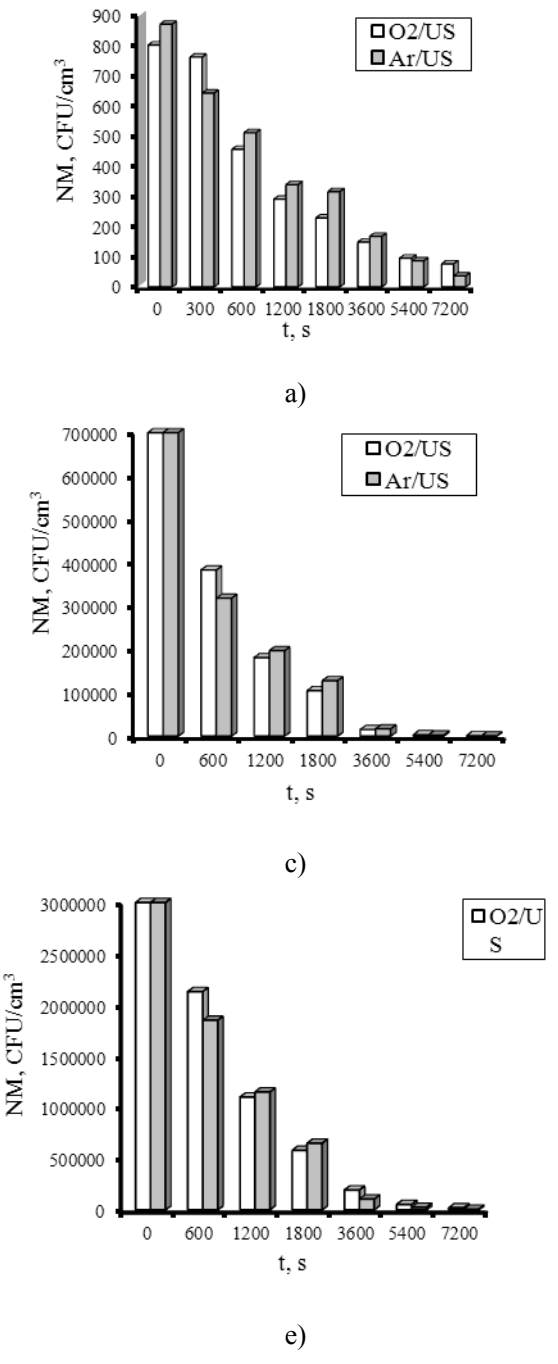

Fig. 1. Dependences of NM values (*Bacillus bacteria*) on the duration of water treatment regimes: Ar/US- and O_2/US-action. Initial data: $8 \cdot 10^2$ CFU/cm^3 – for O_2/US- and $8.69 \cdot 10^2$ CFU/cm^3 – for Ar/US-action (a); $2 \cdot 10^4$ CFU/cm^3 (b), $7 \cdot 10^5$ CFU/cm^3 (c), $1.5 \cdot 10^6$ CFU/cm^3 (d) and $3 \cdot 10^6$ CFU/cm^3 – for O_2/US- and Ar/US-action (e). Process conditions: T = 298 ± 1 K, P = 0.1 MPa

Table 2. The destruction degree of *Bacillus bacteria* depending on the initial number of cells per unit volume of water

The initial number of cells, CFU/cm^3	The D_d value after cavitation and bubbling gas, %	
	in an argon atmosphere	in an oxygen atmosphere
$8\cdot10^2$	*95.9	90.5
$2\cdot10^4$	99.6	98.5
$7\cdot10^5$	99.9	99.8
$1.5\cdot10^6$	99.9	99.9

* The initial data were taken as the value of NM_{max} ($NM_{max} = 8.69\cdot10^2$ instead $8\cdot10^2$ CFU/cm^3), which is due to the detected process of disaggregation during processing with a duration of 300 s

Table 3. Cavitation destruction efficiency of *Bacillus bacteria* in an argon atmosphere

The initial number of cells, CFU/cm^3	R_d	$k_d\cdot10^4$, s^{-1}
$8\cdot10^2$	0.976	*8.92±0.03
$2\cdot10^4$	0.964	8.90±0.04
$7\cdot10^5$	0.997	10.1±0.01
$1.5\cdot10^6$	0.995	9.94±0.01
$3\cdot10^6$	0.998	8.82±0.01

* The initial data were taken as the value of NM_{max} ($NM_{max} = 8.69\cdot10^2$ instead $8\cdot10^2$ CFU/cm^3), which is due to the detected process of disaggregation during processing with a duration of 300 s

Table 4. Cavitation destruction efficiency of *Bacillus bacteria* in an oxygen atmosphere

The initial number of cells, CFU/cm^3	R_d	$k_d\cdot10^4$, s^{-1}
$8\cdot10^2$	0.948	7.47±0.05
$2\cdot10^4$	0.917	8.06±0.08
$7\cdot10^5$	0.993	9.76±0.01
$1.5\cdot10^6$	0.991	9.62±0.02
$3\cdot10^6$	0.991	7.32±0.01

Table 5. Cavitation destruction efficiency of *Bacillus bacteria* in a carbon dioxide atmosphere

The initial number of cells, CFU/cm^3	R_d	$k_d\cdot10^4$, s^{-1}
$(2.2\div2.532)\cdot10^3$	0.977	6.99±0.02
$2.8\cdot10^4$	0.993	7.35±0.01
$8.5\cdot10^4$	0.998	8.68±0.01

Note that in the aqueous phase during microorganism destruction under the action of ultrasonic cavitation, their content is released - water-soluble organic substances.[16,17] The amount of microbial soluble substances in the aqueous medium increases in proportion to the concentration of destroyed cells, as the products of their decay and the products of microorganism activities are molecularly soluble organic compounds of different nature.[17] A significant increase in the concentration of microbial cell decay products in water, released during their mechanical damage by ultrasonic cavitation, obviously inhibits the process of cell destruction. This may explain the slight decrease of D_d value, which was observed at $NM_0 = 3\cdot10^6$ CFU/cm^3 for Ar/US-action (D_d = = 99.8 %), and for O_2/US-action the value of D_d decreased to 99.4 % (Table 2). Therefore, the cause of this phenomenon must be sought in the mechanism of cavitation action at the stage of components oxidation of destroyed microbial cells, products, and intermediates of their activities under cavitation conditions. It can be assumed that the disinfection degree of water under the action of ultrasonic cavitation is determined by the concentration in the water system of decay products of microorganisms and products of their activities.

Calculated by the kinetic equation of the reaction of the first order, the values of the effective rate constants of

the destruction of microorganisms in water for the studied NM_0 after Ar/US action are listed in Table 3 and after O_2/US-action – in Table 4.

Given the fact that carbon dioxide is widely used for microorganism inactivation, disinfection and preservation of water and beverages, it was advisable to study the effect of this gas in cavitation conditions on the change in k_d, depending on the initial number of microorganisms per unit volume of the water system. Working NM_0 for the study of CO_2/US-action in the microbial waters created by us were $(2.2\div2.532)\cdot10^3$; $2.8\cdot10^4$ and $8.5\cdot10^4$ CFU/cm^3. The calculated k_d values, which are also described by the kinetic reaction equation of the first order, are presented in Table 5.

According to Tables 3-5, it is possible to evaluate the cavitation efficiency of bacillary cell destruction, depending on the nature of the bubbled gas, and to construct graphical dependencies. The largest k_d values are calculated for the argon action and the smallest – for carbon dioxide. The dependences $k_d = f(NM_0)$ in the atmosphere of argon, oxygen, and carbon dioxide under cavitation conditions are shown in Figs. 2–3. As we can see, for each gas the region of close k_d values for a relatively wide range of NM_0 values is clearly distinguished. Even with an increase in the value of the NM_0 by almost four orders of magnitude (from $8\cdot10^2$ to $3\cdot10^6$ CFU/cm^3 – for Ar/US and O_2/US) and almost by two orders of magnitude (from $2.2\cdot10^3$ to $8.5\cdot10^4$ CFU/cm^3 – for CO_2/US), the k_d values for each gas vary within close values, but differ in the value depending on its nature:

$$k_{d(Ar/US)} = (9.46\pm0.64)\cdot10^{-4}\ s^{-1};$$
$$k_{d(O2/US)} = (8.54\pm1.22)\cdot10^{-4}\ s^{-1};$$
$$k_{d(CO2/US)} = (7.84\pm0.85)\cdot10^{-4}\ s^{-1}.$$

This indicates that the k_d value does not depend on the NM_0, but is determined by the nature of the bubble gas. On the basis of the presented research the regular number of effective rate constants of bacteria destruction depending on the nature of bubbled gas in the ultrasonic cavitation conditions is established:

$$k_{d(Ar/US)} > k_{d(O2/US)} > k_{d(CO2/US)}.$$

This pattern is explained by different influence of the gas nature on the activity of formation and splashing of caverns in the field of ultrasonic action.

Given the fact that the graphical dependence $k_d = f(NM_0)$ for CO_2/US (Fig. 3) reproduces the nature of the regularity $k_d = f(NM_0)$ for Ar/US and O_2/US (Fig. 2) in the same range NM_0, therefore researches with bigger NM_0 for CO_2/US were not carried out.

Thus, comparing the efficiency of cavitation destruction of *Bacillus bacteria* in the atmosphere of the studied gases (Tables 3–5), the lowest efficiency was found during exposure to carbon dioxide, and the highest – after argon action. That is, experimental data indicate the importance of the gas nature's influence on the efficiency of microorganism inactivation in the cavitation field. To explain these data, it is important to consider certain properties of these gases that may affect the sonochemical activity and explain the result achieved.

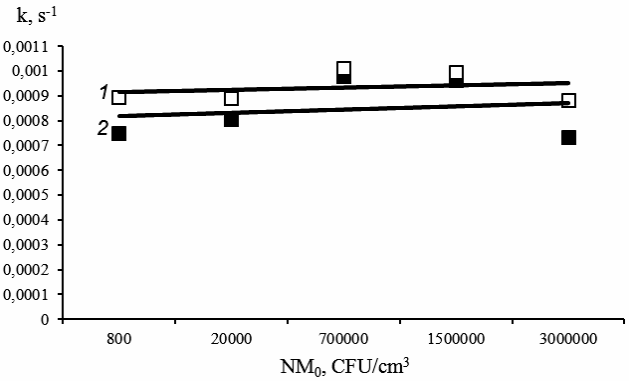

Fig. 2. Dependences of effective rate constants of Bacillus destruction in water with different NM_0 at different modes of water treatment: Ar/US (1) and O_2/US (2). Initial data: NM_0 corresponds to $8\cdot10^2$; $2\cdot10^4$; $7\cdot10^5$; $1{,}5\cdot10^6$ and $3\cdot10^6$ CFU/cm^3

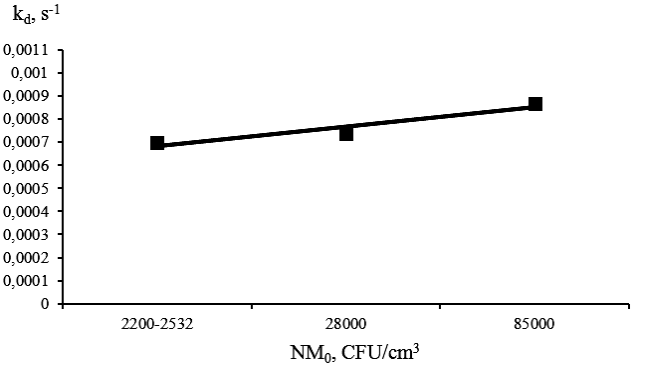

Fig. 3. Dependence of the effective rate constant of the Bacillus destruction with different NM_0 in water under the conditions of CO_2/US-action. Initial data: NM_0 corresponds to $(2.2\div2.532)\cdot10^3$; $2.8\cdot10^4$ and $8.5\cdot10^4$ CFU/cm^3

The lower efficiency of microorganism extinction in the bubbling of carbon dioxide under ultrasonic cavitation conditions, compared with argon and oxygen, can be explained as follows. Carbon dioxide in the processes of water disinfection under the action of ultrasonic cavitation, obviously, inhibits cavitation effects due to the high solubility in water. That is, the process of cracking caverns in the reaction medium is affected by the rate of gas dissolution in the liquid. Dissolved carbon dioxide, penetrating into the cavities, determines the activity of

their splashing, *i.e.*, a significant concentration of dissolved gas slows down the splashing of cavitation bubbles.[1] Carbon dioxide, characterized by high pressure when entering the cavities, probably prevents their drainage, which weakens the cavitation effect in the processes of microorganisms destruction.[3] With increasing solubility of a gas in water, its concentration in the cavity increases, and significant gas penetration into the bubble slows down the rate of its splashing, and as a consequence, reduces the sound and chemical activity of the destruction of the microorganisms in water.

Since the gas dissolution in water is a process that requires a certain duration, the splashing of the cavity in water saturated with carbon dioxide is slower than when bubbling less soluble – oxygen and argon. Such factors suggest a slight influence of the chemical factor under the action of CO_2/US in the processes of cavitational water disinfection.

The highest rates of water disinfection under cavitation conditions were found in an argon atmosphere. Argon, as a monoatomic gas, is more active than a diatomic gas. This is because monohydric gases convert more energy into cavitation than diatomic gases. In addition, argon is characterized by a higher value of the specific heat (for argon $C_p/C_v = 1.667$; for oxygen and carbon dioxide $C_p/C_v = = 1.40$). Therefore, another factor that affects the cavitation collapse of bubbles in the liquid, is because the value of the ratio of C_p/C_v gas depends on the highest temperature that can be reached in the cavity. That is, increasing the ratio of specific heat increases the effective temperature of bubbles, which leads to an increase in the sonolytic yield of radicals that are directly involved in the destruction of cell walls of microorganisms.

Thus, the presented studies allowed not only to describe and evaluate the proposed modes of cavitational water treatment contaminated with microorganisms but also to choose the best methods from the standpoint of high efficiency of the water disinfection process.

4. Conclusions

As a result of the microorganisms identification in the natural and industrial wastewater, their species were identified, indicating the percentage content in 1 cm^3 of water and the predominance of rod-shaped forms of Bacillus cereus bacteria was shown.

The dependences $k_d = f(NM_0)$ after simultaneous ultrasound water treatment and bubbling gases of different nature (carbon dioxide, oxygen, argon) and the degrees of microorganisms destruction for different modes of water treatment with different NM_0 are investigated.

It has been experimentally established that k_d value depends on the gas nature under cavitation conditions but does not depend on the initial number of microorganisms per unit volume of water. During the Ar/US treatment mode, the highest efficiency of bacterial destruction was found, and the lowest – during CO_2/US action, which is reproduced in the following pattern: $k_{d(Ar/US)} > k_{d(O2/US)} > > k_{d(CO2/US)}$. The explanation and substantiation of the gases nature influence on the water disinfection process under cavitation conditions are carried out.

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ВИЗНАЧЕННЯ КОНСТАНТИ ШВИДКОСТІ РУЙНУВАННЯ МІКРООРГАНІЗМІВ ПІСЛЯ УЛЬТРАЗВУКОВОЇ ОБРОБКИ ВОДИ ТА ДІЇ РІЗНИХ ГАЗІВ

Анотація. *Представлено характер зміни числа мікроорганізмів (паличкоподібних споровмісних бактерій роду Bacillus cereus) для діапазону $10^2 \div 10^6$ КУО в 1 см^3 від тривалості одночасної дії ультразвукової (УЗ) кавітації та природи різного газу (вуглекислого газу, кисню, аргону). Зображено графічні залежності величин ефективної константи швидкостей руйнування мікроорганізмів (k_d) від початкової їхньої чисельності в одиниці об'єму води при різних режимах її обробки. Розраховані ступені руйнування бактеріальних клітин у процесі водоочищення. Досліджено, що величина k_d не залежить від початкової кількості клітин у воді, але залежить від природи барботованого газу через реакційне водне середовище:* $\boldsymbol{k_{d(Ar/УЗ)} > k_{d(O2/УЗ)} > k_{d(CO2/УЗ)}}$.

Ключові слова: *дія ультразвуку, процес кавітації, руйнування мікроорганізмів, кисень, вуглекислий газ, аргон.*