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INVESTIGATIONS OF CAVITATION PROCESSES IN DIFFERENT TYPES OF EMITTERS USING SONOCHEMICAL ANALYSIS

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Abstract. The application limits of optical and sonochemical methods to determine the sizes of cavitation bubbles and their derivatives have been analyzed. The effect of cavitation fields generated using an ultrasonic magnetostrictive oscillator and jet hydrodynamic emitter on the parameters of their acoustic signals has been examined. The bubbles size depending on emitter type and parameters has been determined using sonochemical analysis. The character of the dependence was estimated according to Minnaert formula. The bubbles dispersity in the flotation zone may be controlled by varying conditions of cavitation excitation.

Keywords: cavitation, flotation, bubble, sonochemical method, acoustic signal, resonance, frequency spectrum, wastewater treatment.

1. Introduction

The intensification of liquid-phase media purification is an urgent problem for many technological processes, especially for waste waters treatment in the food and processing industries (meal-processing, dairy, wine industries, *etc*.). The existing technologies do not provide necessary degree of waters purification from organic substances and suspended fine pollutants, demand expensive reagents (coagulants, flocculants). They are multistaged, power-consuming, harmful for the environment, and economically ineffective [1, 2]. Thus the development of new technological processes for waters treatment using the achievements in other fields of science, such as energetic or acoustic ones, is the key point.

The combination of known purification methods (mechanical, physico-chemical, biological) and different methods of power influence on the disperse medium (water) and disperse phase (pollutants) is the promising direction of technologies development. Cavitation is the most effective method of power influence. The initiation of cavitation processes provides the formation of high-amplitude short-term impulses and allows to concentrate the energy of these impulses in discrete local areas intensifying the purification process [3-6]. Thus, for instance, the application of high-voltage short-term impulses (≤ 150 μm) to treat the flotation solutions of concentration plants resulted in the reduction of dispersed particles deposition time from 54 to 7 h, suspended substances content – from 35 to 2.5 mg/dm^3, pH value – from 9.60 to 7.82. The optimum power consumption for medium treatment is 5.1 kJ/dm^3 [7].

Taking all the above-mentioned into account, the authors developed the concept of cavitation-flotation process of waste waters treatment implying a series of successive interrelated processes: excitation of cavitation resulted in pollutants conversion, generation of cavitation bubbles and their further use for the flotation of organic substances and suspended fine pollutants [8]. It is well-known that flotation efficiency is determined by air bubbles size, amount, stability and uniformity of their distribution in waste water [9-11]. Therefore, the aim of present work is to investigate the dependence of cavitation field parameters (size of cavitation bubbles, pattern of cavitation area, its volumetric-spatial development, *etc*.) on emitter type and characteristics.

2. Experimental

2.1. Theoretical part

The optical and sonochemical methods are widely used to determine the sizes of micro- and nanoparticles.

The essence of optical methods is to measure the intensity of light scattered by dispersed particles. By means of laser diffraction based on Fraunhofer theory, in particular its statement about diffraction at the particle boundaries and constant coefficient of extinction, only small scattering angles (under 14°) are taken into consideration, which restricts the use of the method by particle size of about 1μm. To consider optical properties of the particles Mie theory is used. It describes the radiation for all spatial directions and around homogeneous spherical particles in homogeneous, non-absorbing medium, and argues that light scattering is based on phenomenon of resonance - coincidence of the particle oscillation frequency and frequency of light wave. According to Mie theory there are several possible vibrational states with different probability and there is a relation between the optically active section and particle size, length of the light wave and refractive indices of the particle and medium. Therefore, to use Mie theory refractive index and absorption coefficients of particles and medium should be known [12]. These data are often not available, which restricts the use of optical techniques and makes it necessary to use other methods for determining particle size, sonochemical methods in particular.

Sonochemical methods are also based on phenomenon of resonance. In the field of acoustic waves the gas (air) bubble pulses and its radius spreads about the mean with the frequency of incident wave. At a definite frequency the oscillations convert to resonance ones with maximum amplitude [13]. If the pulsation is an adiabatic process, the Minnaert formula [14] is used to describe the ratio between resonance frequency and bubble radius.

$$w = \frac{1}{2p\, R_b}\sqrt{\frac{3g\, P_0}{r}}, \qquad (1)$$

where w – resonance frequency, Hz; R_b– bubble radius, m; g – adiabatic exponent (1.4 for the air); P_0 – hydrostatic pressure at the liquid surface, Pa ($P_0 = 10^5$ Pa); r – liquid density, kg/m^3.

So, the bubble radius and resonance frequency are inversely proportional values, *i.e.* with the increase in resonance frequency the bubble radius decreases. The change of resonance frequency characterizes the change of bubbles size and, hence, the peculiarities of generated cavitation fields (their homogeneity, spatial localization, *etc.*) and properties of the flotation layer, its density in particular. While analyzing operation principles of different emitters (magnetostrictive or hydrodynamic) it may be predicted that oscillation frequency of cavitation bubbles depends on method of cavitation excitation.

2.2. Practical Part

Cavitation fields were generated by ultrasonic magnetostrictive oscillator "Ultrasonic Disintegrator UD-20" with the oscillation frequency of 22 kHz and jet hydrodynamic emitter with nozzles of various diameters placed under fixed angle. The emitter frame (diameter 110 mm and height 1000 mm) is made from transparent organic glass allowing visualization of the process, as well as photographing and filming. In our previous investigations [15] we determined the conditions under which the most effective usage of the supplied energy is realized (coefficient of efficiency was 88.9 %): number of cavitation elements (nozzles) – 3; nozzle diameter – 1.6 mm; angle between nozzle axes – 50 deg. Pump drive of the jet emitter was 1.1 kW. The inlet pressure (within the range of 0.35–0.57 MPa) was controlled using by-pass. We measured temperature of outlet water, its pH value (using pH-meter of 150 M type with the combined electrode ESKL-08M 1) and redox potential (using universal ionometer EV-74 with platinum pickup electrode EVP-1 and chlorine-silver reference electrode EVL-1 M). The determined properties of outlet water were: temperature – 291 ± 1 K, pH – 7.51, redox potential – 225 mV.

The cavitation fields in different emitters (ultrasonic or hydrodynamic) were compared using sonochemical analysis. The characteristics of acoustic signals were measured using spherical hydrophone of 8105 type commuted with computer. Hydrophone operating range is within 0.1 Hz – 160 kHz, sensitivity – 205 (dB rel. 1V)/μPa. The advantage of spherical hydrophone is its special structure providing vibration insulation of the sensitive element [16].

Oscillograms of acoustic signals, spectra of frequency and intensity were recorded using Adobe Audition 1.5 programs.

3. Results and Discussion

Oscillogram of acoustic signal in the cavitation field generated by ultrasonic magnetostrictive oscillator is represented in Fig. 1. The "0 dB" level of acoustic signal corresponds to the maximum possible amplitude of the peaks under which the signal fixing is still possible.

The level of acoustic signal (acoustic noise) in the cavitation field generated by ultrasonic oscillator during first 15 min of treatment is considerably higher (by 2–2.5 times) than during next 10 min. Moreover, the increase in emitter capacity decreases the period between two adjacent amplitude values of the signal. The reason is formation of individual cavitation bubbles in aqueous medium, their pulsations (duration 0–15 min, Fig. 1) and coalescence under the action of Bjerknes forces. Bjerknes forces are forces of electrostatic adhesion occurred between air spherical bubbles pulsated in the liquid. The average with time Bjerknes force (F, N) is calculated as [17]:

$$F = \frac{r\,\Omega_1\Omega_2 \cos y}{4p\, l^2} \qquad (2)$$

where r – liquid density, kg/m^3; $\Omega = 4pR_b^2 w$ – volume rate of the pulsating bubble, m^3/s; y – difference between bubbles oscillation phases; l – distance between bubbles, m.

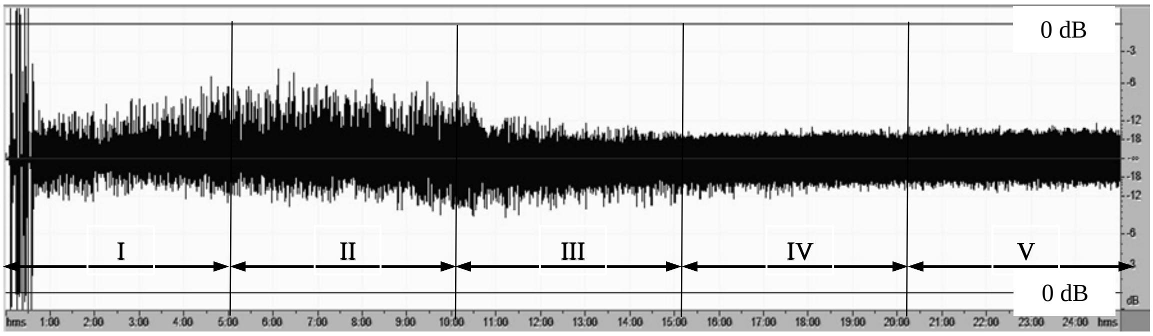

Fig. 1. Oscillogram of acoustic signal of the cavitation field generated by the magnetostrictive oscillator. Emitter capacity (W) changed with time (min): 8.0 (I); 9.2 (II); 10.2 (III); 11.5 (IV) and 12.5 (V)

Whereas the concentration of cavitation bubbles (bubbles of the I generation) over the magnetostrictor increases with time, the distance between bubbles decreases. According to Eq. (2) it leads to the increase in Bjerknes force and bubbles coalescence. As a result, one or several agglomerates of bubbles (agglomerate – a bubble of the II generation) are formed, the diameter of which may achieve even 10 m. This agglomerate of bubbles is called large deformated bubble (LDB) [18].

Taking into account that in the case of ultrasonic oscillator the cavitation field is localized around the working surface of magnetostrictor, the process of cavitation field formation may be assumed as quasiheterogeneous one, *i.e.* it depends on surface area of magnetostrictor (Fig. 2). Thus, at the same amount of supplied energy and equal treatment time the number of cavitation bubbles, as well as size, homogeneity and density of cavitation fields enhance with the increase in magnetostrictor surface area.

The decrease in resonance frequency with the increase of emitter capacity (Figs. 3 and 4, Table 1) indicates the grouping of bubbles of the I generation and formation of agglomerates.

With increasing emitter capacity from 8.0 to 12.5 W the amplitude value of acoustic pressure shifts toward the field of low frequencies – from 3800 to 1763 Hz (Fig. 4). The value of resonance frequency was assumed as arithmetic mean of four frequencies corresponding to the amplitude values of acoustic signal during definite period of time (Table 1).

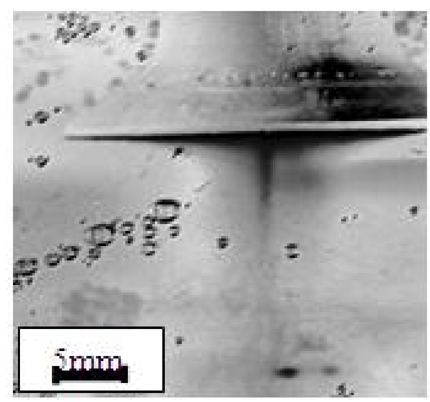

Fig. 2. Photograph of the cavitation field generated by ultrasonic magnetostrictive oscillator (inverted image)

In accordance with Minnaert formula (1), the decrease of resonance frequency indicates the increasing radius of bubbles of the I generation (0.86 mm) followed by their coalescence and formation of bubbles of the II generation with the average radius of 1.86 mm. Further increase in emitter capacity does not change the bubbles size. If we decrease the capacity, bubbles dispersion increases but productivity relative to gas phase considerably decreases.

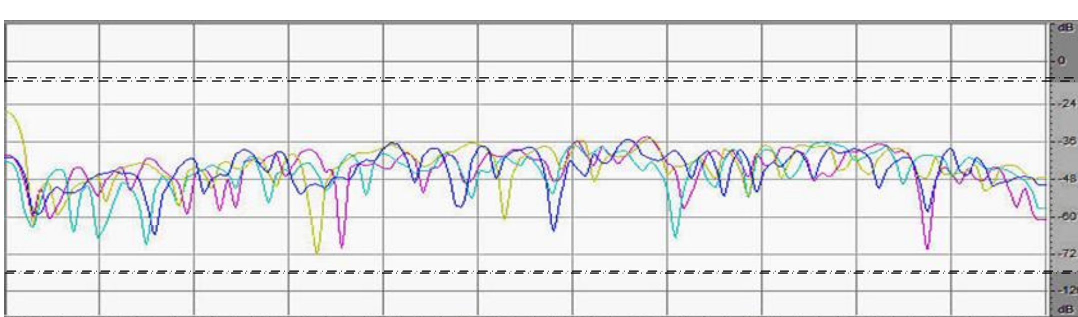

Fig. 3. Frequency spectrum at emitter capacity of 12.5 W

Table 1

Resonance frequencies depending on emitter capacity

Emitter capacity, W	Cavitation treatment time, s / Amplitude values of frequency, Hz				Resonance frequency, Hz
8.0 (period I)	60	120	180	240	3800
	4900	4400	2500	3400	
9.2 (period II)	360	420	480	540	2650
	2950	2200	2300	3150	
10.2 (period III)	660	720	780	840	1993
	1620	3800	1400	1150	
11.5 (period IV)	960	1020	1080	1140	1768
	500	3400	1870	1300	
12.5 (period V)	1260	1320	1380	1440	1763
	1750	750	1650	2900	

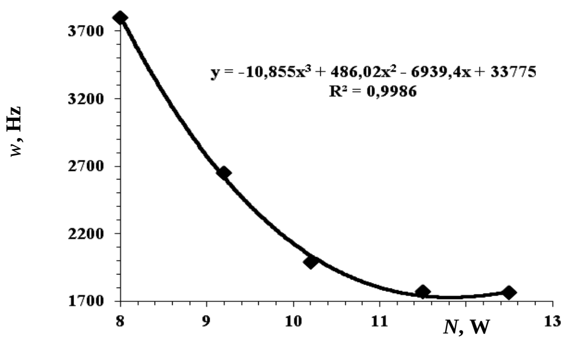

Fig. 4. Resonance frequency (*w*, Hz) *vs*. capacity of ultrasonic oscillator (*N*, W)

Oscillogram of acoustic signal in the cavitation field generated by jet hydrodynamic emitter is represented in Fig. 5.

The pressure increase at the emitter inlet from 0.29 to 0.57 MPa increases the acoustic signal from -7 to -4 (dB rel 1V)/μPa. It is connected with the development of cavitation because the formation of cavitation cluster is visually observed at the inlet pressure of 0.35 MPa.

Polydispersed system with bubbles different by size is formed at hydrodynamic cavitation unlike acoustic one. With the increasing pressure at the emitter inlet the share of bubbles with small size increases. The increase in bubbles resonance frequency confirms this fact (Fig. 6, Table 2). Thus, with increasing pressure from 0.35 to 0.57 MPa the amplitude value of acoustic pressure shifts toward the field of high frequencies – from 1760 to 4025 Hz (Fig. 7). The same as for ultrasonic emitter, the value of resonance frequency was assumed as arithmetic mean of four frequencies corresponding to the amplitude values of acoustic signal during definite period of time (Table 2).

The increase of resonance frequency with the increase of inlet pressure from 0.35 to 0.57 MPa indicates partial size reduction of the cavitation bubbles with the radius of 1.87 mm and formation of their derivatives with the radius of 0.83 mm. The analysis of resonance frequency, as well as bubbles size dependence on the pressure in cavitation element allows to affirm that bubbles dispersion increases with further increase of the pressure (Fig. 7). For example, at the pressure of 1 MPa the calculated size of bubbles will equal to 35 μm. Thus, it will be possible to control flotation in the jet hydrodynamic emitter.

Generation of cavitation fields with bubbles of different sizes and possibility to control a part of fine-dyspersated bubbles is an essential advantage of jet hydrodynamic emitter compared with ultrasonic magnetostrictive emitter. Moreover, the value of acoustic signal of cavitation field generated by hydrodynamic emitter is four times larger than that of ultrasonic emitter (-4 and -16 (dB rel. 1V)/μPa, respectively, Figs. 1 and 5). The mentioned values are obtained at maximum values of supplied energy, *i.e.* at inlet pressure of 0.57 MPa for hydrodynamic emitter and capacity of 12.5 W for ultrasonic emitter.

The results clearly demonstrate different structures of the cavitation fields generated by different emitters.

The intensity spectrum of acoustic signal of cavitation field generated by jet hydrodynamic emitter is represented in Fig. 8.

As it is known, the greater amplitude of acoustic signal component within a specified frequency range, the brighter the color [19]. The brightest color has a spectrum area within the frequency range from 1 to 1.5 kHz for emitter inlet pressure 0.41–0.57 MPa. Probably, the above-mentioned fact can be explained by the presence of vortex formations, the intensity of which increases with increasing inlet pressure in the emitter. They contribute to dispersion of generated cavitation bubbles (bubbles of the I generation) and their possible aggregates with bubbles of dissolved gases in the liquid column over cavitation element (bubbles of the II generation). When the liquid flow with the dispersed bubbles passes up, bubbles size decreases. The formation of three zones – cavitation, transient and flotation ones are observed in hydrodynamic emitter. Thus, two technological stages (cavitation and flotation) are combined in the same apparatus. In first zone the bubbles of specified size (1.87 mm) are generated due to cavitation. The particularity of the transient zone is occurrence of vortex flows caused by various nonstationarities (gradients of pressure and rate relative to apparatus section, occurrence of local gas-liquid flows, *etc*.). With the approach to flotation zone vortex flows are destroyed as a result of interaction with a liquid moved with lower rate. Then the formation of fine bubbles with the radius of 0.83 mm (bubbles of the III generation) is observed in flotation zone. The color of the system becomes milky caused by high-dispersed bubbles accumulation. This is especially true in the case of introducing small amounts of air (1% relative to the volume of treated water), which serves as cavitation nuclei and greatly intensifies the development of cavitation fields.

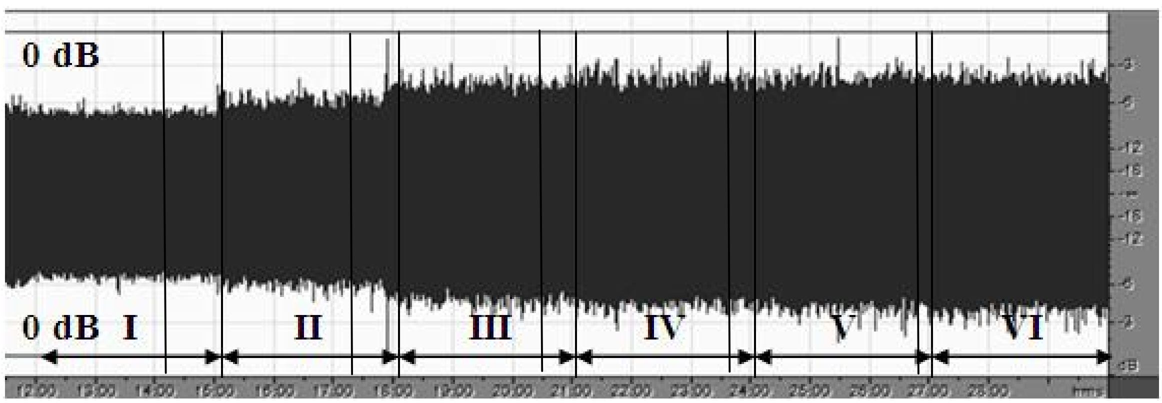

Fig. 5. Oscillogram of acoustic signal of the cavitation field generated by jet hydrodynamic emitter. Emitter pressure (MPa) changed with time (min): 0.29 (I); 0.35 (II); 0.41 (III); 0.53 (IV) and 0.57 (V)

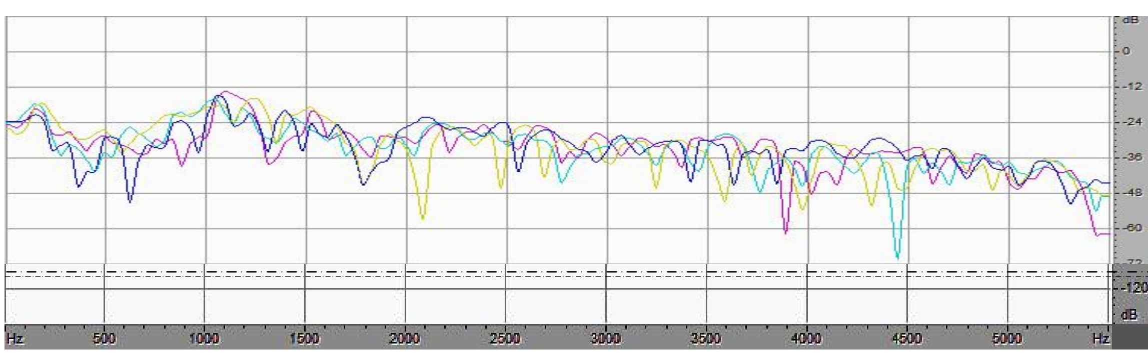

Fig. 6. Frequency spectrum of acoustic signal of the cavitation field generated by jet hydrodynamic emitter with inlet pressure of 0.57 MPa

Table 2

Resonance frequencies depending on inlet pressure of jet hydrodynamic emitter

Inlet pressure, MPa	Cavitation treatment time, s				Resonance frequency, Hz
	Amplitude values of frequency, Hz				
0.35 (period II)	750	780	810	840	1760
	970	1750	2800	1520	
0.41 (period III)	1110	1140	1170	1200	2300
	1850	1800	3500	2050	
0.47 (period IV)	1290	1320	1350	1380	2605
	2150	3750	2220	2300	
0.53 (period V)	1470	1500	1530	1560	3083
	3780	1300	3800	3450	
0.57 (period VI)	1650	1680	1710	1740	4025
	3900	4450	3950	3800	

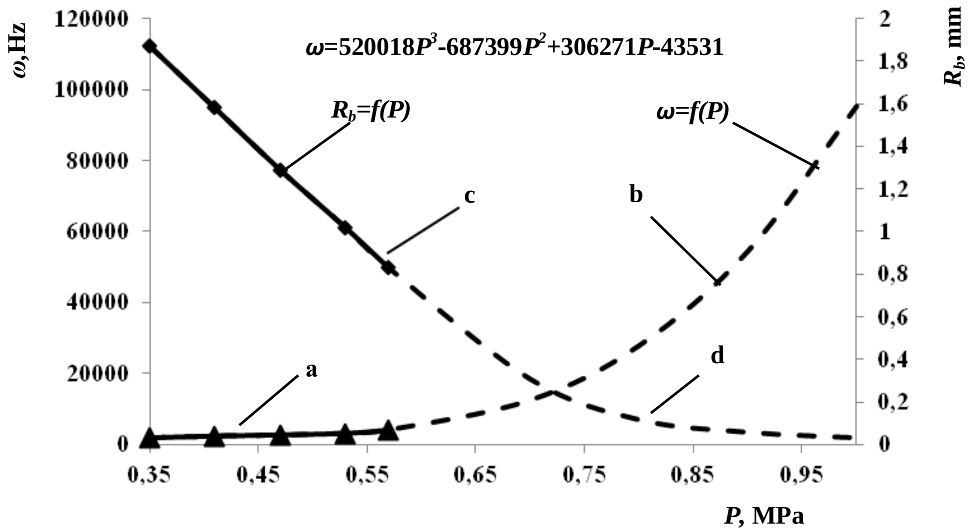

Fig. 7. Resonance frequency (*w*, Hz) and bubble radius (R_b,mm) *vs*. inlet pressure (*P*, MPa): experimental (a, b) and theoretical values (c, d)

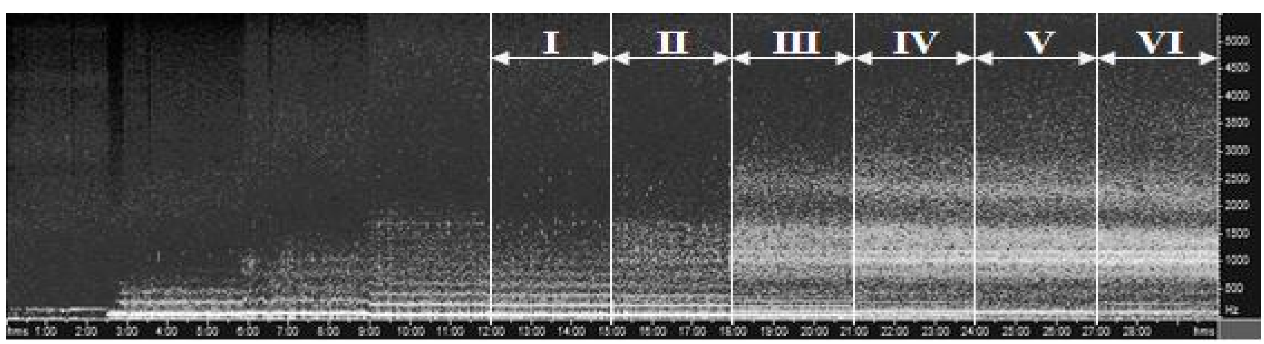

Fig. 8. Intensity spectrum of acoustic signal of the cavitation field generated by jet hydrodynamic emitter. Emitter inlet pressure (MPa) changed with time (min): 0.29 (I); 0.35 (II); 0.41 (III); 0.53 (IV) and 0.57 (V)

Visually it was found that cavitation field generated by the hydrodynamic emitter covered the entire reaction volume. It is more homogeneous, dense and contains larger number of fine bubbles compared with the field generated by ultrasonic emitter. Therefore we can assert that it will provide more efficient flotation of organic pollutants and suspended fine substances. In addition, the increase of medium pH and reduction of the redox potential (to 7.59 and 200 mV, respectively, for ultrasonic emitter and to 8.35 and 127 mV, respectively, for hydrodynamic emitter) indicate desorption of dissolved carbon(IV) oxide and water sonolysis followed by recombination of hydrogen radicals to form molecular hydrogen [20]. These processes also provide active flotation of pollutants.

4. Conclusions

1. To determine the size of fine bubbles (to 10^{-6}–10^{-9} m), especially in polluted and waste waters sonochemical methods should be used. They are based on measuring the resonance frequency of air bubbles oscillation and Minnaert formula for calculations.

2. Cavitation field generated by ultrasonic emitter is localized near emitter surface, so its formation may be considered as a quasi-heterogeneous process. With the increase in emitter capacity the shift of acoustic pressure amplitude toward the area of low frequencies (from 3800 to 1763 Hz) indicates a growing radius of bubbles of the I generation (0.86 mm), their subsequent coalescence under the action of Bjerknes forces and formation of bubbles of the II generation with the radius of 1.86 mm.

3. With increasing inlet pressure in hydrodynamic emitter from 0.35 to 0.57 MPa the acoustic pressure amplitude shifts toward high frequency area (1760–4025 Hz), *i.e.* the dispersion of bubbles increases (radius decreases from 1.87 to 0.83 mm).

4. The acoustic signal value of cavitation field generated by hydrodynamic emitter is 4 times greater compared to that of ultrasonic emitter (-4 and -16

(dB rel. 1V)/μPa). This indicates more intensive formation of fine bubbles.

5. Three zones – cavitation, transient and flotation – are formed in jet hydrodynamic emitter. Bubbles size is gradually reduced in the zones, enabling to combine two stages (cavitation and flotation) of waste water treatment in one apparatus.

6. Cavitation field generated by hydrodynamic emitter covers the entire reaction volume. It is more homogeneous, dense and contains larger number of fine bubbles than cavitation field generated by ultrasonic emitter. Therefore it will provide more efficient flotation of organic pollutants and suspended fine substances.

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ДОСЛІДЖЕННЯ КАВІТАЦІЙНИХ ПРОЦЕСІВ У ГЕНЕРАТОРАХ РІЗНИХ ТИПІВ МЕТОДОМ СОНОХІМІЧНОГО АНАЛІЗУ

Анотація. *Проаналізовано межі застосування оптичних та звукохімічних методів визначення розмірів кавітаційних бульбашок та їх похідних. Досліджено вплив кавітаційних полів, сформованих за допомогою ультразвукового магнітострикційного випромінювача та гідродинамічного струменевого кавітатора, на параметри акустичних сигналів, що їх характеризують. Залежність розмірів кавітаційних бульбашок у полях від типу генераторів та параметрів їх роботи зафіксовано з використанням методу сонохімічного аналізу, а її характер оцінено за формулою Міннерта. Показано, що контрольованою зміною умов збудження кавітації можна регулювати дисперсність бульбашок у флотаційній зоні, що необхідно для вилучення із рідкофазних середовищ частинок різних розмірів.*

Ключові слова: *кавітація, флотація, бульбашки, звукохімічні методи, акустичний сигнал, резонанс, спектр частот, очищення стічних вод.*