Determination of Optimum Conditions of Ultrasonic Cavitation Treatment of High-viscous and Non-newtonian Liquid Media

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***Abstract* – The article presents the results of theoretical and experimental studies aimed at the determination of optimum conditions of the ultrasonic action (geometry of the technological volume) for the cavitation treatment of high-viscous and non-Newtonian liquids. Developed model of the generation of the cavitation area lets determine distribution of the cavitation zone in the technological volumes of various sizes and forms. Carried out experimental studies allow prove adequacy of the proposed model and possibility to increase the volume of developed cavitation zones by the optimization of the conditions of ultrasonic action.**

***Index Terms* – Ultrasound, cavitation, viscosity, non-Newtonian medium.**

I. INTRODUCTION

LIQUID AND liquid-dispersed media, which are characterized by essential viscosity (uncured nanostructured polymer materials, varnish-and-paint blend compositions, resins), are widely used in industry. The application of such media as a raw material allows impart unique properties to the final product (high strength of polymer composite materials exceeding steel strength, biocidal properties of lacquer coatings, etc.). It can be achieved by the modification of physical-chemical structure of liquids. Numerous laboratory researches [1,2] prove that the most promising modification method of the physical-chemical structure of original high-viscous liquid and liquid-dispersed media in order to improve properties and characteristics of the final product is the ultrasonic cavitation action.

For instance, in the paper [1] it was determined; that the treatment of epoxy resin EPO by ultrasonic vibrations with the intensity of 100 W/cm^2 during 5 minutes led to the decrease of its viscosity in 48% due to the destruction of polymer macromolecules. It in turn improves impregnating property of resin. The introduction of various nanomodifiers [2] to polymers by ultrasonic action leads to the increase of ultimate strength of final material at bending in 20% and at compression in 30%.

Appointed effects at the ultrasonic influence are caused by the generation of collapsing gas-and-steam bubbles (cavitation phenomenon) in liquid media, which form high-amplitude shock waves (with pressure amplitude of no less than $8 \cdot 10^6$ Pa in the front) leading to breaking of the molecular bonds, acceleration of mass carry processes, etc.

However in spite of positive results of the laboratory studies ultrasonic cavitation treatment of high-viscous liquid media, which can be non-Newtonian in some cases (with the dependence of viscosity on shear rate), is not practically realized in industry due to small volume and concentration of the cavitation area near the surface of the ultrasonic radiator.

At that for the generation of the cavitation zone with the volume, which is necessary for industrial treatment of liquids, even intensities of ultrasonic vibrations (more than 70 W/cm^2) close to ultimate theoretical strength of the waveguide-radiators are insufficient. Designed at present the multizone working tools with developed radiating surface do not provide the solution of the concentration of the cavitation zone near the radiating surface. That is why the most promising approach to the volume increase of formed cavitation zone is the optimization of the conditions of ultrasonic action (the geometry of the technological volume) providing the generation of standing waves. At the generation of standing waves summation of incident and reflected waves occurs, that allows increase the amplitude of ultrasonic pressure (intensity of ultrasonic vibrations) in no less than two times in all area of liquid. It leads to the rise the area zone, in which intensity of ultrasonic vibrations exceeds some threshold value required for the formation of the developed cavitation zone [2] that increases the volume of this zone. Thus the efficiency increase of ultrasonic treatment of high-viscous and non-Newtonian liquids can be provided.

II. PROBLEM DEFINITION

To determine optimum conditions of ultrasonic action it is necessary to solve a number of particular tasks:

1. Develop phenomenological model of the formation of cavitation area in non-Newtonian liquid allowing determine the form and the size of the cavitation zone in a liquid medium at different modes of the cavitation development.
2. Determine the dimensions of the technological volumes providing the increase of the volume of formed cavitation area at ultrasonic treatment of liquids with the application of developed model.
3. Study experimentally the conditions of cavitation area formation in order to prove obtained theoretical results.

For the solution of the first task we design the model of the cavitation area formation in non-Newtonian liquids, which is described further.

III. THEORY

The building block of the model of the cavitation area is the generalized equation of cavitation bubble dynamics in non-

Newtonian liquid (under its compressibility) given in the paper of the scientists of the University of Wales [3]:

$$R\frac{\partial^2 R}{\partial t^2}\left(1-\frac{\frac{\partial R}{\partial t}}{C}\right)+\frac{3}{2}\left(\frac{\partial R}{\partial t}\right)^2\left(1-\frac{\frac{\partial R}{\partial t}}{3C}\right)=$$
$$=H\left(1+\frac{\frac{\partial R}{\partial t}}{C}\right)+\frac{\partial H}{\partial t}\frac{R}{C}\left(1-\frac{\frac{\partial R}{\partial t}}{C}\right)-$$
$$-\frac{1}{\rho_\infty}\left(1+\frac{\frac{\partial R}{\partial t}}{C}\right)\int_R^\infty\left(\frac{\partial\tau_{rr}}{\partial r}(r)+\frac{3\tau_{rr}}{r}(r)\right)\partial r+ \quad ; \quad (1)$$
$$+\frac{1}{\rho_\infty}\frac{R}{C}\left(\frac{\partial\tau_{rr}}{\partial r}\left(R,\frac{\partial R}{\partial t}\right)+\frac{3\tau_{rr}\left(R,\frac{\partial R}{\partial t}\right)}{R}\right)\frac{\partial R}{\partial t}$$

where τ_{rr} is the radial tensor component of viscous liquid stress, Pa; R is the instantaneous radius of the cavitation bubble, m; H is the enthalpy of liquid, m^2/s^2, C is the local acoustic speed in liquid, m/s; ρ_∞ is the steady-state density of continuous liquid, kg/m^3; r is the distance from the center of the cavitation bubble, m.

Function $\tau_{rr}\left(R,\frac{\partial R}{\partial t}\right)$ is defined by three characteristics of rheological properties of liquid: initial viscosity μ_0 (Pa·s), consistency K (Pa·s^{N+1}) and non-linearity N indices. At that depending on rheological properties, which influence mainly on the cavitation process, liquids are divided into *linear-viscous* (the viscosity does not depend on the shear rate, N=0), *pseudoplastic* (the viscosity decreases with the rise of shear rate, N<0) and *dilatant* (the viscosity increases with the growth of shear rate, N>0).

Proposed approach to the solution of the equation (1) based on independent examination of the phases of bubble expansion and collapse lets determine the dependence of bubble radius R (t, I) on time t and intensity of ultrasonic vibrations I at the first stage. At next stage with the use of equation of cavitation bubbles coalescence and breaking [4] the stationary concentration $n_\infty(I)$ and instantaneous volume content of the bubbles $\delta(t,I)=\frac{4}{3}\pi R^3(t,I)n_\infty(I)$ depending on time and intensity of ultrasonic vibrations.

On the base of obtained data (volume content of the cavitation bubbles) we find the distribution of intensities with the help of solution of the wave equation (2):

$$\Delta\left(\sqrt{2\rho c I(\mathbf{x})}e^{i\varphi(\mathbf{x})}\right)+$$
$$+\frac{\omega^2}{c_0{}^2}\left(1-\frac{\rho_0 c_0{}^2\,\overline{\delta_1}\left(\sqrt{2\rho c I(\mathbf{x})}e^{i\varphi(\mathbf{x})}\right)}{\sqrt{2\rho c I(\mathbf{x})}e^{i\varphi(\mathbf{x})}}\right)\times; \quad (2)$$
$$\times\sqrt{2\rho c I(\mathbf{x})}e^{i\varphi(\mathbf{x})}=0$$

where I is the intensity of ultrasonic vibrations, W/m^2; φ is the phase shift of vibrations of acoustic pressure in liquid; ω is the circular frequency of the initial ultrasonic field, s^{-1}; c_0 is the acoustic speed in a continuous liquid, m/s; ρ_0 is the steady-state density of continuous liquid, kg/m^3; ρ is the density of cavitating liquid, kg/m^3; c is the acoustic speed in cavitating liquid, m/s; $\overline{\delta_1}\left(\sqrt{2\rho c I(\mathbf{x})}e^{i\varphi(\mathbf{r})}\right)$ is the complex amplitude of the change of volume content of the cavitation bubbles relative to mean value, **x** is the radius-vector of liquid, m.

The distribution of intensities of ultrasonic vibrations defined by the equation (2) at known geometry of the ultrasonic radiator and technological volume allows determine the distribution of cavitation zones in the volume of processed liquid.

It can be achieved by the analysis of determined functional dependence of the radius of the cavitation bubble $R(t,I)$ on time t and intensity of ultrasonic vibrations I. Further subject to the behavior of the cavitation bubble in a course of time in each point of liquid (according to the functional dependence $R(t,I)$) at obtained distribution of intensities $I(\mathbf{x})$ we ascertain forms and positions of the cavitation zones in the technological volume corresponding to the following modes:

1) *the mode of cavitation absence,* in which there is no bubbles collapse (movement rate of the bubble walls does not exceed speed of sound in continuous liquid – 1500 m/s);

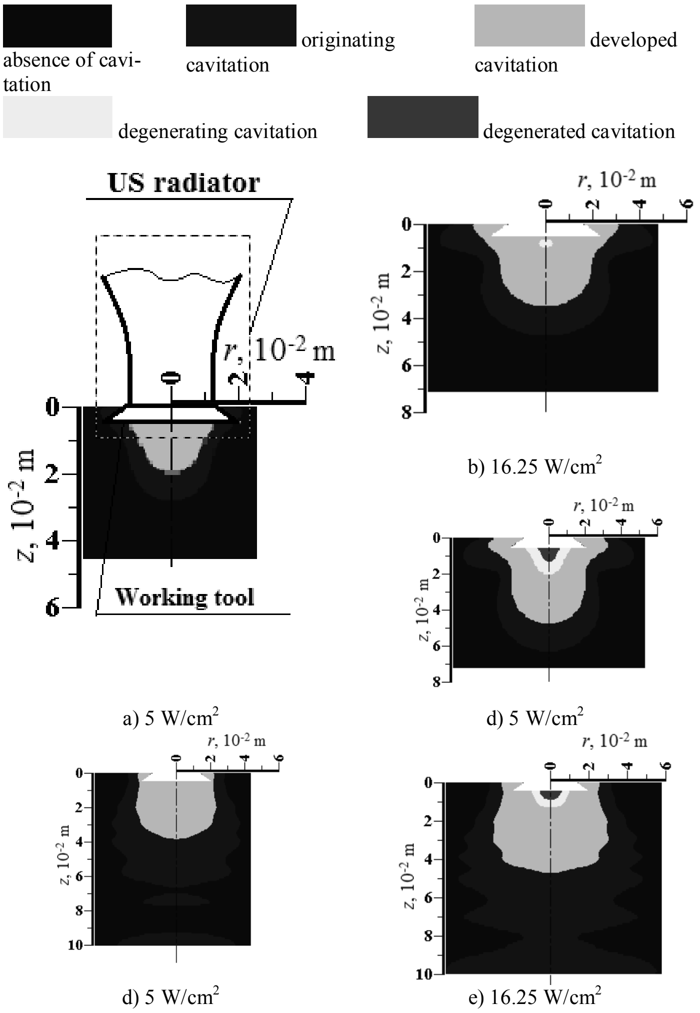
2) *the mode of originating cavitation* – collapse of the bubbles occur at low amplitudes of shock wave pressure (less than 20·10^5 Pa), and the level of intensification of physical-chemical processes in liquids under the action of ultrasound is negligibly small;

3) *the mode of developed cavitation* – bubbles collapse takes place with maximum amplitudes of shock waves pressure (20·10^5…80·10^5 Pa); as a criteria of the mode of developed cavitation is the presence of damage of aluminum foil of 9 μm under the action of cavitation;

4) *the mode of degenerating cavitation* – intensity of bubbles collapse decreases in comparison to the mode of developed cavitation, and bubbles as a rule make radial vibrations without collapse during 2 periods of initial ultrasonic wave and more from the moment of initial widening;

5) *the mode of degenerated cavitation* – bubbles collapse does not occur, and they make radial vibrations in the neighborhood of larger radius (no less than 300 μm).

Fig. 1 a-c shows the forms and the dimensions of the cavitation zone in a plane of symmetry of the ultrasonic radiator corresponding to five described above modes of cavitation development for different intensities of ultrasonic action in an unlimited volume without reflectors. The viscosity of model liquid is 100 mPa·s, the model type of the ultrasonic radiator is piston-type (the diameter of the working tool is 40 mm). From Fig. 1 a-c it is evident, that starting with 16.25 W/cm² for the model liquid the zone of developed cavitation does not enlarge. It means that the efficiency of the ultrasonic equipment decreases, when intensity of ultrasonic action exceeds optimum value. That is why it is necessary to create conditions for optimum distribution of ultrasonic pressure, for instance by the design of the volumes with reflecting surfaces (Fig. 1c-d).



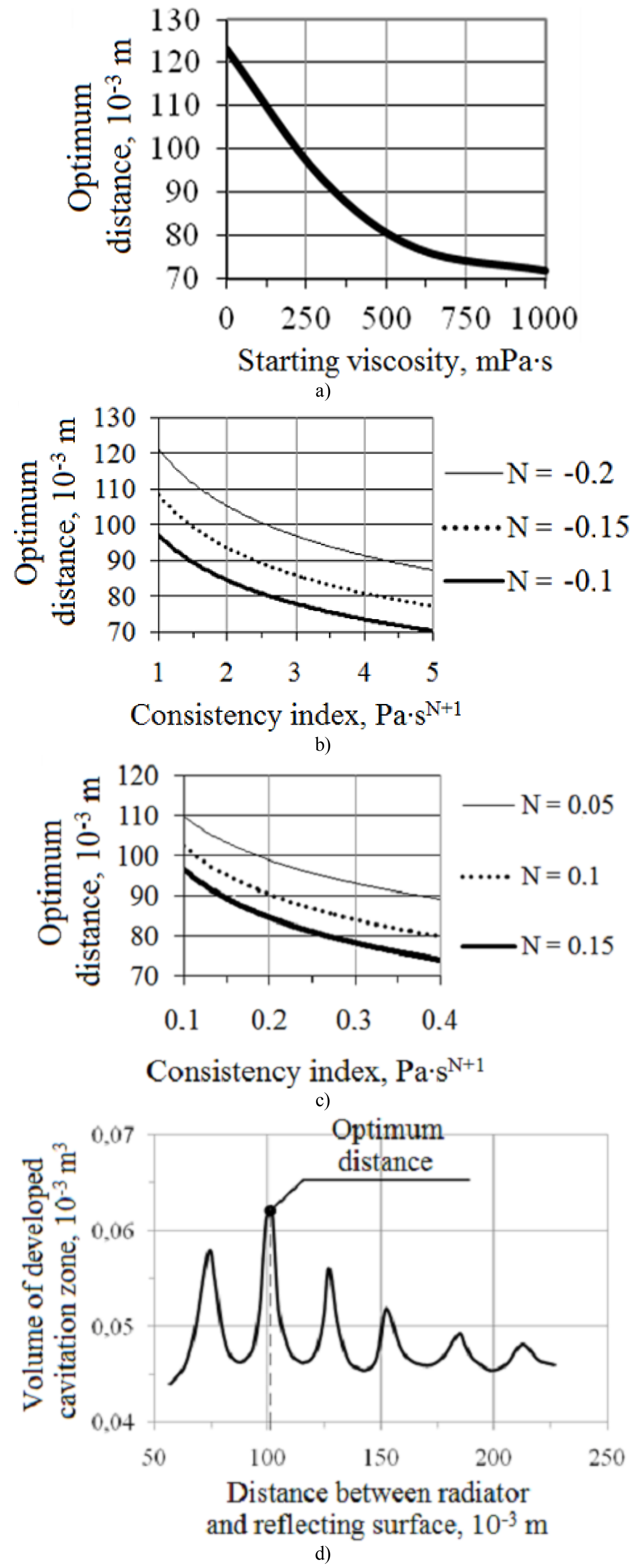
a) 5 W/cm^2 b) 16.25 W/cm^2 d) 5 W/cm^2 d) 5 W/cm^2 e) 16.25 W/cm^2

Fig. 1. Distribution of cavitation zones in liquid with the viscosity of 100 mPa·s for different intensities of ultrasonic action generated near the radiating surface (*r* is the distance from the acoustic axis of the radiator, *z* is the length of the cavitation zone

As it follows from Fig. 1d-e, at the presence of reflecting wall the zone of developed cavitation increases in more than 0.5 cm in length and it becomes wider in 1.2…1.3 times, that points at the possibility of the increase of developed cavitation zone in 1.3…1.4 times due to the summation of incident and reflecting waves.

It is evident, that there is an optimum distance, at which the volume of developed cavitation zone will be maximum. The presence of optimum distance can be explained by the fact, that at small distances between the radiator and reflecting wall the total volume of processed liquid becomes small, and at large distances (when the distribution of the cavitation zone is close to the distribution generated at the absence of the reflecting border) the zone of developed cavitation is concentrated near the radiating surface (Fig. 1a-c). The concentration of the developed cavitation zone near the radiating surface is caused by high absorption coefficient of ultrasonic waves in cavitating liquid exceeding 20 dB/m.

Fig. 2a-c shows the dependences of optimum distance on the rheological properties of liquids. The presence of optimum distance, at which effective volume (with the developed cavitation) is maximum, it can be illustrated by the dependence of the volume of the developed cavitation zone on the distance between the radiating surface and the reflecting border shown in Fig. 2d (the viscosity of the model liquid is 100 mPa·s, the intensity of ultrasonic action is 11.25 W/cm^2).



a) b) c) d)

Fig. 2. Dependences of optimum distance between the radiating surface and the reflecting border on the indices characterizing rheological properties of liquids: a) linear-viscous; b) dilatant; c) pseudoplastic; and dependence of the volume of developed cavitation zone on the distance (d)

To verify obtained dependences we carry out a number of the experiments aimed at the determination of the volume of generated cavitation zone subject to the distance between the radiator and the reflecting border.

IV. EXPERIMENTAL RESULTS

The experimental studies were made with the application of the test bench shown in Fig. 3.

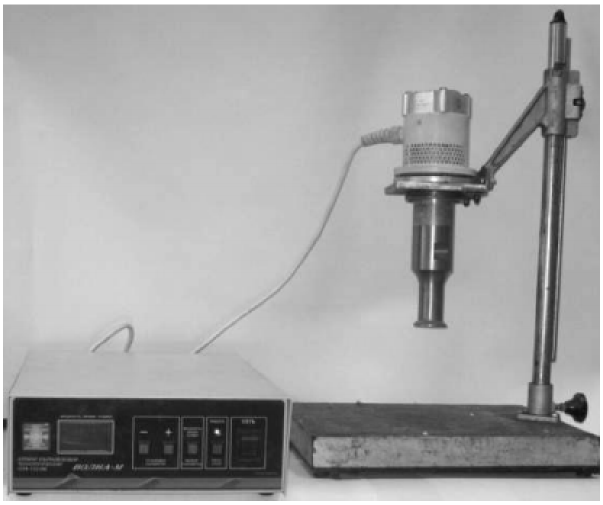


Fig. 3. Experimental test bench for the determination of the dependence of the volume of developed cavitation zone on the distance between the radiator and the reflecting border

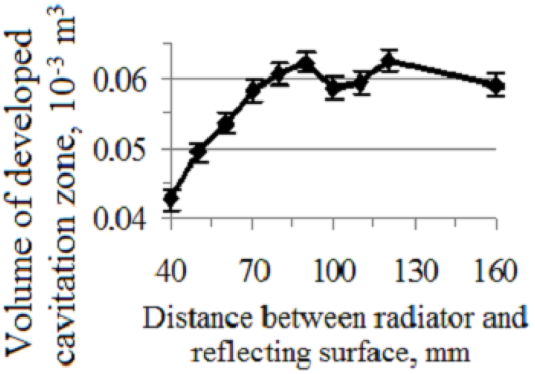
Experimental determination of the volume of developed cavitation zone was made on the base of the estimation of erosive activity of the cavitation zone on damage of test samples of aluminum foil (with the thickness of 9 μm).

Obtained experimental dependences of the volume of developed cavitation zone on the distance between the radiating surface and the reflecting border for liquids different in viscosity are shown in Fig. 4. Obtained experimental values of maximum achieved volume of developed cavitation zone and optimum distances between the radiator and the reflecting surface for liquid s different in rheological properties are summarized in Tab. I.

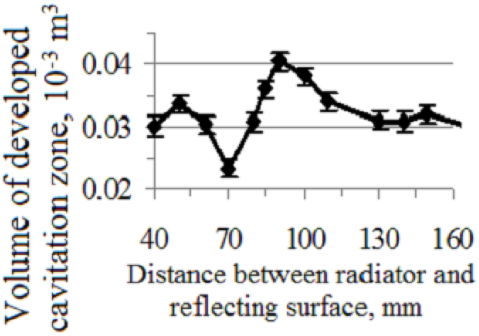
TABLE I

EXPERIMENTAL VALUES OF THE VOLUMES OF DEVELOPED CAVITATION ZONE AND OPTIMUM DISTANCES BETWEEN THE RADIATOR AND THE REFLECTING SURFACE

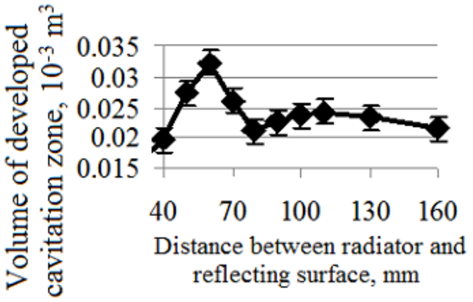
Name of liquid		Water	Oil	Epoxy resin ED-5
Experimental values of the volume of developed cavitation zone, 10^{-3} m^3	**At optimum distance between the radiator and the reflector**	0.062576	0.04044	0.032212
	Without the reflector	0.057227	0.0319	0.021382
Values of optimum distances between the radiating surface and the reflecting border	**Experimental, L_E, 10^{-3} m**	123	102	71
	Theoretical, L_T, 10^{-3} m	120	90	60
	Relative error, $\lvert L_T-L_E\rvert\cdot100/L_E$, %	2.5	13.3	18.3



a) water (the viscosity is 1 mPa·s, the intensity of ultrasonic action is 3 W/cm^2)



b) oil (100 mPa·s, 7.5 W/cm^2)



c) epoxy resin ED-5 (the initial viscosity is 520 mPa·s, the consistency index K=3.9 Pa·s^{N+1}, nonlinearity index N=-0.15, the intensity is 25 W/cm^2)

Fig. 4. Dependences of the volume of developed cavitation zone on the distance between the radiator and the reflecting border for different liquids

Obtained results (see Fig. 4, Tab. I) prove the possibility of the increase of the volume of developed cavitation zone up to 51% (for instance, for epoxy resin ED-5 with the initial viscosity of no less than 0.5 Pa·s) by the optimization of the distance between the radiator and the reflecting border at constant intensity of action. At that according to Tab. I the relative error between theoretical and experimental values of the optimum distance does not exceed 15% that proves the adequacy of proposed model.

V. CONCLUSION

Thus proposed model of the cavitation zone generation let study the influence of the conditions of propagation and reflection of ultrasonic vibrations on total volume occupied by the zone of the most efficient cavitation action and develop the construction of the technological chamber providing the efficiency increase of ultrasonic treatment. The model allowed determines optimum distance between the border of the technological volume and the radiator providing the increase of the volume of developed cavitation zone in more than 50%. It was shown, that optimum distance was in the range of 50 – 125 cm, and it fell with the increase of liquid viscosity.

Carried out experimental studies proved the adequacy of proposed model of the formation of the cavitation zone and the possibility of the increase of the volume of developed cavitation zone by the optimization of the distance between the radiating surface and the reflecting border.

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