# Process Modeling of Cavitation Zone in the Technological Volumes with High-viscous and Fine-dispersed Liquid Media

Roman N. Golykh, *Student Member, IEEE,* Vladimir N. Khmelev, *Senior Member, IEEE,* Sergey S. Khmelev
*Biysk Technological Institute (branch) Altai State Technical University named after I.I. Polzunov, Biysk, Russia*

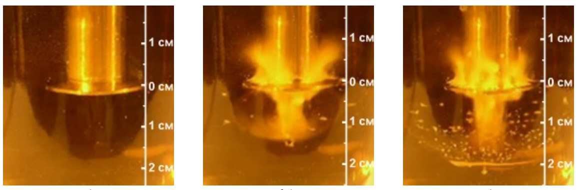
***Abstract* – In the article the results of theoretical investigations aimed at reveal of possibilities of providing maximum size of cavitation zone in limited volumes during ultrasonic influence on technological media having high viscosity or high concentration of dispersed phase are presented. To find out optimum conditions (geometrical dimensions and forms of technological volume) and modes (intensity) of ultrasonic influence on different in viscosity and acoustic properties of liquid mathimatical modeling of the dynamics of the cavitating medium was carried out. Proposed approach to the modeling is based on numerical steam-gas-liquid medium developed on well-known models of microscopic process of extension and collapse of single cavitation bubble. Obtained results allow to recommend the choice of specialized technological volumes and optimum intensities of influence.**

***Index Terms* – ultrasound, cavitation area, viscosity, technological volume, impedance of the medium, acoustical absorption.**

## I. INTRODUCTION

IMPOSSIBILITY OF ULTRASONIC INTENSIFICATION OF THE PROCESSES in high-viscous and dispersed media is the reason of absence of industrial ultrasonic equipment, which is able to provide high-intensity influence necessary for the mode of developed cavitation in them. Existing theoretical and experimental investigations [1-3] are the evidence of the fact, that for epoxy resin it is necessary to have the intensity of ultrasonic influence up to 30 W/cm$^2$.

Moreover in the case of realization of such method due to the use of the concentrator – amplifiers having radiating surface of small diameter, the processed area will be limited not only by the size of radiating surface, but also by small size of the cavitation zone. For instance, the cavitation zone generated during ultrasonic procesing of epoxy resin can be seen during the experiments (as it is shown in Fig. 1).



a) b) c)

Fig. 1. Photos of cavitation in epoxy resin in different periods of time: a) 0 s; b) 3 s; c) 9 s

As it is evident from the photos, if the diameter of radiating surface is 25 mm, the cavitation zone (longitudinal size) at the initial stage does not exceed 15 mm in 3 sec and 20 mm in 9 sec. Thus longitudinal size of the cavitation zone does not exceed the diameter of the radiator, and with time magnification of the longitudinal size of the cavitation zone occurs owing to decrease of viscosity because of temperature rise of epoxy resin.

It is clear that the absence of cavitation outside the isolated area is explained by lowered amplitudes of sound pressure not enough for generation of steam and gas pockets.

That is why, it is necessary to increase intensity of radiation in order to set required amplitude of pressure fluctuations of the medium in maximum possible part of the technological volume.

However intensity growth does not provide essential increase of cavitation zone (productivity of the process), as it ignores the influence of the size and form of the technological volume on the generation of cavitation cloud. At the same time it is possible to bound longitudinal size of the processed volume for generation of standing waves, which, as it is known, due to the influence of reflective effects lead to more even distribution of acoustic energy in the technological volume. In the traveling-wave mode the most energy is concentrated near the surface of the working tool of the ultrasonic vibrating system.

Thus to increase the efficiency of ultrasonic influence it is necessary to acomplish combined optimization of the value of of longitudinal size of processed volume and intensity of influence, which allow to generate maximum in size cavitation zone at minimal power inputs, i.e. to provide optimum mode and conditions of ultrasonic influence.

For solving this task and for understanding of the process mathematical modelling of the generation of the cavitation zone in viscous media under the influence of ultrasonic vibrations should be realized. The mathematical model will allow to carry out complex optimization of the ultrasonic cavitation processing of high-viscous liquid media, i.e. to reveal potimum modes and conditions of ultrasonic influence.

## II. PROBLEM STATEMENT

The most part of theoretical studies on modelling of ultrasonic cavitation is devoted to the theory of motion of single cavitation bubble [4-7]. While in practice during ultrasonic cavitation processing of viscous liquid media in the closed technological volumes we deal with cavitation zone, i.e. with aggregation of numbers of interacting bubbles different in their size. Propagation of sound in heterophase media, for instance, liquid with gas or steam bubbles, cavitation zone, swirl, upper layers of ocean having large amount of cavitation bubbles has the following feautures [8]:

– gas, steam and steam-gas bubbles cause acoustic wave scattering;

– energy dissipation of acoustic field occurs due to the work on extention of cavitation pockets. At that at the stage of cavitation bubble collapse it partly transforms into the energy of shock wave, which is completely lost from the energy of initial ultrasonic wave transforming into thermal energy [8].

Mentioned features lead to fast attenuation of ultrasonic wave, which amplitude in the cavitation zone (in a plane wave) decays according to ordinary exponential law $p_{\max} = p_{\max 0} e^{-\alpha_{\text{cav}} x}$, but with c attenuation coefficient $\alpha_{\text{cav}}$, which considerably exceeds absorption coefficient of subcavitating liquid. As a result of this attenuation in acoustically infinite medium pressure amplitude in ultrasonic wave decrases up to threshold value necessary for generation of cavitation and cavitation ends.

Thus to optimize in a whole ultrasonic processing of high-viscous liquid media several special tasks should be solved:

– to analyse the influence of sound scattering and te work on extension of cavitation pockets on the value of ultrasonic wave absorption;

– to obtain the equation or develop the system of equations with boundary conditions describing the process of propagation of sound in cavitating liquid;

– to carry out analitical and numerical calculations of the acoustic field and the sizes of cavitation zone in processed at different intensities of ultrasonic influence and in different technological volumes.

In order to simplify theoretical analysis of cavitation it is necessary to adopt following assumpion:

– steam and gas bubbles retain spherical form during their radial oscillations;

– wave length $\lambda$ (60…100 mm) is much longer than the distance between bubbles $l$ (0.1…3 mm), which in turn is more than radius of the cavitation bubble $R$ (1…300 μm), $\lambda >> l >> R$.

Next parts of the article are devoted to solving problems put by.

## III. THE ANALYSIS OF DYNAMICS OF SINGLE BUBBLE UNDER THE INFLUENCE OF ACOUSTIC PRESSURE

To find out the character of generated cavitation zone in different technological volumes it is necessary to carry out theoretical studies of dynamics of single cavitation pocket under the unfluence of acoustic vibrations.

Numerous results of theoretical and experimental investigations [5, 8] show, that radial vibrations of the cavitation bubble formed under the influence of ultrasound have complex spectral distribution and acoustic radiation made by it appears in the form of broadband noise with the spectrum in band from several hundreds of Hz to hundreds of kHz. Spectrum anaysis of signal waveform by Fourier series expansion allows to separate spectrum lines corresponding to the main frequencyof influence $f_0$, its harmonics $nf_0$ (n=1, 2, 3), subharmonics $nf_0/2$, $nf_0/3$, $nf_0/4$ and ultraharmonics of pocket vibrations. Acoustic pressure appears in the form of short impulses generated at collapse of pockets, at that time their spectrum is a continuous function. Besides main frequency and harmonics of high frequency $nf_0$ (n=1, 2, 3, ...) there are series of subharmonics in the spectrum $nf_0/2$, $nf_0/3$, $nf_0/4$, and in all range flat random noise occurs.

For theoretical detection of the spectrum of radial vibrations of cavitation bubble following Nolting-Nepayres equation [5] describing dynamics of cavitation pocket in viscous liquid should be used:

$$\rho\left(\frac{3\dot{R}^2}{2}+R\ddot{R}\right)=-\frac{2\sigma}{R}+p_{g0}\left(\frac{R_0}{R}\right)^{3\gamma}-4\eta\frac{\dot{R}}{R}-p_\infty \qquad (1)$$

In high-viscous liquids in view of necessity to use high acoustic pressure for maintanance of cavitation [1-3] it should be considered correct, that the processes of extension and collapse of single cavitation bubble take place during the period in wide range of intensities of influence (Fig. 2) up to 25 W/cm$^2$.

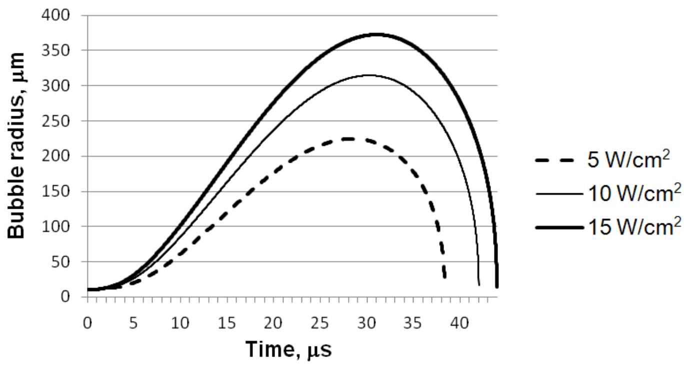



Fig. 2. Dependences of cavitation bubble radius on time in olive oil at different intensities of influence (5… 15 W/cm$^2$) at the frequency of 22 kHz (vibration period 45 μs)

This fact lets consider fluctuations of radius of single cavitation bubble in viscous liquid at stationary mode of periodic extension and collapse with the period, which equals to the period of the fundemental harmonic, i.e. the assumption of subharmonic absence is accepted. According to this assumption the function representing dependence of radius of the cavitation pocket on time $R(t)$ can be presented in view of Fourier decomposition:

$$R(t) = R_0 + \sum_{n=1}^{\infty}\left(R_n e^{in\omega t} + R_n^* e^{-in\omega t}\right)$$

At harmonic analysis of cavitation pocket vibrations the radius is approximately presented in the form of the sum of the first $N$ harmonics:

$$R(t) = R_0 + \sum_{n=1}^{N}\left(R_n e^{in\omega t} + R_n^* e^{-in\omega t}\right) \quad (2)$$

After substitution of the expression (2) into the equation (1) we have:

$$-\frac{3\left[\sum_{n=1}^{N} n\left(R_n e^{in\omega t} - R_n^* e^{-in\omega t}\right)\right]^2}{2} -$$
$$-\left[R_0 + \sum_{n=1}^{N}\left(R_n e^{in\omega t} + R_n^* e^{-in\omega t}\right)\right] \times$$
$$\times \sum_{n=1}^{N}\left[n^2\left(R_n e^{in\omega t} + R_n^* e^{-in\omega t}\right)\right] =$$
$$= -\frac{2\sigma}{\omega^2\left[R_0 + \sum_{n=1}^{N}\left(R_n e^{in\omega t} + R_n^* e^{-in\omega t}\right)\right]} +$$
$$+ \frac{p_{г0}}{\omega^2}\left(\frac{R_{0b}}{R_0 + \sum_{n=1}^{N}\left(R_n e^{in\omega t} + R_n^* e^{-in\omega t}\right)}\right)^{3\gamma} -$$
$$-\frac{4\eta}{\omega^2}\frac{\sum_{n=1}^{N} in\omega\left(R_n e^{in\omega t} - R_n^* e^{-in\omega t}\right)}{R_0 + \sum_{n=1}^{N}\left(R_n e^{in\omega t} + R_n^* e^{-in\omega t}\right)} - \frac{p_\infty}{\omega^2} \quad (3)$$

Further numerical analysis of system of equations for each harmonic $n=1...N$, which is obtained from the equation (3) with the use of property of linear independence of the functions $e^{in\omega t}$ is made.

## III. Influence of sound scattering on the value of acoustic wave attenuation

At falling sound wave the single bubble making forced vibrations partly reraradiates (dissipates) energy of sound-wave falling at it. If there are many bubbles in liquid, each of them is in the field of both fallen and scattered waves from near bubbles, which generate the field of multiple scattering, causing absorption of initial acoustic wave. To evaluate the absorption caused by scattering the following simple model is proposed.

Wave field in the medium with $N$ bubbles can be written as the sum of initially propagating sound wave and the set of scattered waves of monopolistic type (4):

$$p(r) = p_m\left(e^{i(\mathbf{k},\mathbf{r})} + \sum_{n=1}^{N} f_n \frac{e^{ik|\mathbf{r}-\mathbf{r}_n|}}{|\mathbf{r}-\mathbf{r}_n|}\right) \quad (4)$$

Under the assumption $\lambda >> L >> R$ the approximate values of unknown coefficients $f_n$ are simply expressed by the product of falling field $p_n^l(r)$ to $n$- bubble and scattering amplitude on the single bubble $f_1$ (5):

$$p_n^l(r) = p_m\left(e^{i(\mathbf{k},\mathbf{r})} + f_1 \sum_{n=1,\, n\neq l}^{N} p_n^l(r_n)\frac{e^{ik|\mathbf{r}-\mathbf{r}_n|}}{|\mathbf{r}-\mathbf{r}_n|}\right) \quad (5)$$

It should be noted, that in ordinary liquids the bubbles are located in an arbitrary random manner. If each of $N$ bubbles occupies in the volume $V$ any equally probable place independent from other scatters, ensemble averaging of any random variable $p(r)$ of configurations should be made according following rule []:

$$\overline{p(r)} = \frac{N}{V}\int p(r_1, r_2, ..., r_N)\,dr_1 dr_2 ... dr_N \quad (6)$$

At averaging of the equation (5) according to the rule (6) under the assumption that the field falling on $l$-bubble does not depend on the coordinates of $l$-scatter. If it occurs that scattering at each bubble is small, then average falling field near any of $N$ bubbles can be substituted for approximately equal to it total average $\overline{p(r)}$. After such notes and appropriate operations we have so-called Dajson equation [8] for medium field or so-called equation of self-consistent field (4):

$$\overline{p(r)} = p_m e^{ikr} + f_1 n\int \frac{e^{ik|r-r'|}}{|r-r'|}\overline{p(r')}\,dr' \quad \textbf{(7)}$$

After application of Helmholtz operator $\Delta + k^2$ to the both parts of integral equation after number of transformations we have following equation (5) (Laplace operator $\Delta$ proposes $r$ differentiation):

$$\left(\Delta + k^2\right)\overline{p(r)} = \left(\Delta + k^2\right)\left[p_m e^{ikr} + f_1 n\int \frac{e^{ik|r-r'|}}{|r-r'|}\overline{p(r')}\,dr'\right]$$
$$\left(\Delta + k^2\right)\overline{p(r)} = -4\pi\left[f_1 n\int \delta\left(|r-r'|\right)\overline{p(r')}\,dr'\right]$$
$$\left(\Delta + k^2 + 4\pi f_1 n\right)\overline{p(r)} = 0 \quad (5)$$

The equation (5) can be considered as an anologue of Helmholtz equation with some effective wave number

$$k_{\text{eff}}^{\;2} = k^2 + 4\pi f_1 n$$

where $k$, $k_{eff}$ and $f_1$ are in the general case complex values.

To evaluate the value $f_1$ the process of radial vibrations of the single cavitation bubble in uniform (depending a little on coordinates, in view of $\lambda >> L >> R$) field of sound pressure is considered.

Amplitude of acoustic pressure near the walls of cavitation pocket is defined as:

$$p \approx -\rho\frac{\partial\varphi}{\partial t} = -\rho\frac{\partial}{\partial t}\left(\frac{R^2\frac{\partial R}{\partial t}}{R_0}\right) =$$

$$= -\rho\frac{\partial}{\partial t}\left(\frac{\left[R_0 + \sum_{n=1}^{N}\left(R_n e^{in\omega t} + R_n^* e^{-in\omega t}\right)\right]^2\left[\sum_{n=1}^{N} in\omega\left(R_n e^{in\omega t} - R_n^* e^{-in\omega t}\right)\right]}{R_0}\right) \sim$$

$$\sim f_1\left(p_l e^{i\omega t} + p_l^* e^{-i\omega t}\right)$$

Coefficients $R_1$, ... , $R_N$ are defined on the base of harmonic analysis of equation (6).

## III. INFLUENCE OF INPUT ON THE WORK FOR EXTENSION OF CAVITATION POCKETS ON THE VALUE OF ACOUSTIC WAVE ABSORPTION

Approach to revelation of absorption coefficient is based on the use of energy conservation law in the integral form for continuous medium.

In the unit of volume of liquid under study potential energy of sound wave will equal $\frac{c^2\rho_l}{2\rho_0}$, where c is the adiabatic sound velocity, $\rho_l$ is the perturbed liquid density under the influence of ultrasonic vibrations, $\rho_0$ is the equilibrium density;

the work expended for the extension of the pocket in a reversible way under the action of pressure of saturated steam of liquid — is the current radius of the cavitation bubble, $R_0$ is the radius of the nucleus;

kinetic energy of liquid motion caused by extension and collapse of the cavitation pockets — $\frac{3}{2}\rho_0 bR^3\dot{R}^2$;

energy of acoustic waves radiated by pulsating pockets — $-\frac{2\rho_0 b}{c}R^3\dot{R}^3$;

potential energy of cavitating liquid caused by compressibility of bubbles in perfect liquid— $-b\rho_l\frac{p_0}{\rho_0}\left(R^3 - R_0^3\right)$, where $p_0$ is the static pressure of liquid;

kinetic energy of liquid in acoustic wave — $\frac{\rho_0 u^2}{2}$, u is the speed of liquid motion.

The expression for energy of acoustic wave in the medium with cavitation bubbles is following:

$$\iiint_V\left(\frac{c^2\rho_l}{2\rho_0} - bp_n\left(R^3 - R_0^3\right) + \frac{3}{2}\rho_0 bR^3\dot{R}^2 - \frac{2\rho_0 b}{c}R^3\dot{R}^3 - b\rho_l\frac{p_0}{\rho_0}\left(R^3 - R_0^3\right) + \frac{\rho_0 u^2}{2}\right)dV$$

Mean full energy flux through the surface of cavitating liquid equals:

$$\oiint\left(\overline{p_m u} - \overline{bp_0\left(R^3 - R_0^3\right)u} + \overline{\frac{3}{2}\rho_0 ubR^3\dot{R}^2} - \overline{\frac{2\rho_0 ub}{c}R^3\dot{R}^3} - \overline{ubp_n\left(R^3 - R_0^3\right)}\right)$$

Mentoned above relations let to consider true following expression for energy conservation law of ultrasonic wave in integral form:

$$\iiint_{\omega_t}\frac{\partial}{\partial t}\left(\frac{c^2\rho_l}{2\rho_0} + \frac{3}{2}\rho_0 bR^3\dot{R}^2 - \frac{2\rho_0 b}{c}R^3\dot{R}^3 - b\rho_l\frac{p_0}{\rho_0}\left(R^3 - R_0^3\right) + \frac{\rho_0 u^2}{2}\right)dV =$$

$$= -\oiint_{\partial\omega_t}\left(\overline{p_m u} - \overline{bp_0\left(R^3 - R_0^3\right)u} + \overline{\frac{3}{2}\rho_0 ubR^3\dot{R}^2} - \overline{\frac{2\rho_0 ub}{c}R^3\dot{R}^3}\right)$$

where $\omega_t$ is separated volume of liquid in instant of time $t$, $\partial\omega_t$ isboundary surface of the volume $\omega_t$.

In one-dimensional case at the presence of plane wave:

$$\frac{\partial}{\partial t}\left(\overline{\frac{3}{2}\rho_0 bR^3\dot{R}^2}\right) = -\frac{\partial}{\partial x}\left(\frac{\overline{p_m^2}}{2\rho c}\right)$$

At the damping $p_m = p_{m0}e^{-\alpha x}$ there is:

$$\frac{\partial}{\partial t}\left(\overline{\frac{3}{2}\rho_0 bR^3\dot{R}^2}\right) = \frac{\alpha\overline{p_m^2}}{\rho c} \quad (8)$$

From the equation (8) it is possible to state the value of absorption coefficient caused by expenditures on work for the extension of the cavitation pockets.

## IV. COMPUTING METHOD OF ACOUSTIC FIELD IN CAVITATING LIQUID

The task of finding of amplitude distribution of acoustic pressure in cavitation zone in the mode of developed cavitation is reduced to the solution of Helmholtz equation by finite element method on the base of revealed cavitation absorption coefficient.

The Helmholtz equation will have following form:

$$\Delta p + k_*^2 p = 0 \quad (9)$$

where $k_*$ is the effective wave number, which equals to $k_* = k + ik_{**}$.

At the consideration of the process of generation of cavitation zone in the cylindrical technological volume the equation (9) is solved in cylindrical coordinate system.

At modeling by finite element method following finite-element approximation is used.

$$p = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1}\alpha_{mn}N_{mn}(z,r)$$

$$N_{mn}(z,r) = f_n(z)g_m(r)$$

If it is assumed, that the step along the axis z of the cylinder equals $h_1$, and the distance from the axis of the cylinder is $h_2$, in that case the basis functions $f_k$ and $g_m$ will be following:

$$f_k(z) = \begin{cases} 0, \text{ если } z < (k-1)h_1 \text{ или } z > (k+1)h_1 \\ \dfrac{z-(k-1)h_1}{h_1}, \text{ если } z \ge (k-1)h_1 \text{ и } z < kh_1 \\ \dfrac{(k+1)h_1 - z}{h_1}, \text{ если } z \ge kh_1 \text{ и } z \le (k+1)h_1 \end{cases}$$

$$g_m(r) = \begin{cases} 0, \text{ если } r < (m-1)h_2 \text{ или } r > (m+1)h_2 \\ \dfrac{r-(m-1)h_2}{h_2}, \text{ если } r \ge (m-1)h_2 \text{ и } r < mh_2 \\ \dfrac{(m+1)h_2 - r}{h_2}, \text{ если } r \ge mh_2 \text{ и } r \le (m+1)h_2 \end{cases}$$

Integral about a closed surface is transformed in a following way:

$$\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\alpha_{kl}\iiint_V \left[k_*^2 N_{mn}N_{kl} - (\nabla N_{mn},\nabla N_{kl})\right]dV = i\omega \oiint_S N_{mn}\rho(\mathbf{U},\mathbf{n})\partial S$$

It should be noted, that the integral $\iiint_V \left[k_*^2 N_{mn}N_{kl} - (\nabla N_{mn},\nabla N_{kl})\right]dV$ is nonzero only in the case, when $|m-k|\le 1$ and $|n-l|\le 1$.

Thus the task is reduced to the solution of the system of equatons with block-tridiagonal matrix:

$$\begin{bmatrix} A_1 & B_1 & O & O & \dots & O & O \\ B_1 & A_2 & B_2 & O & & \dots & O \\ O & B_2 & \dots & \dots & & & \dots \\ O & O & \dots & \dots & & O & O \\ \dots & \dots & & & & B_{M-2} & O \\ O & \dots & & O & B_{M-2} & A_{M-1} & B_{M-1} \\ O & O & \dots & O & O & B_{M-1} & A_M \end{bmatrix} \times \begin{bmatrix} \alpha_{00} \\ \alpha_{01} \\ \dots \\ \alpha_{0N-1} \\ \alpha_{10} \\ \dots \\ \alpha_{M-1N-1} \end{bmatrix} = i\omega\rho \begin{bmatrix} \oiint_S N_{00}(z,r)(\mathbf{U},\mathbf{n})\partial S \\ \oiint_S N_{01}(z,r)(\mathbf{U},\mathbf{n})\partial S \\ \dots \\ \oiint_S N_{0N-1}(z,r)(\mathbf{U},\mathbf{n})\partial S \\ \oiint_S N_{10}(z,r)(\mathbf{U},\mathbf{n})\partial S \\ \dots \\ \oiint_S N_{M-1N-1}(z,r)(\mathbf{U},\mathbf{n})\partial S \end{bmatrix} \quad (10)$$

The solution of the system of linear equation (10) aloow to find coefficients $\alpha_{00}$ and $\alpha_{M-1N-1}$ completely determining amplitude distribution of acoustic pressure.

## V. OBTAINED RESULTS OF PTIMIZATION

The dependence of the damping coefficient on viscosity of liquid is shown in Fig. 3.

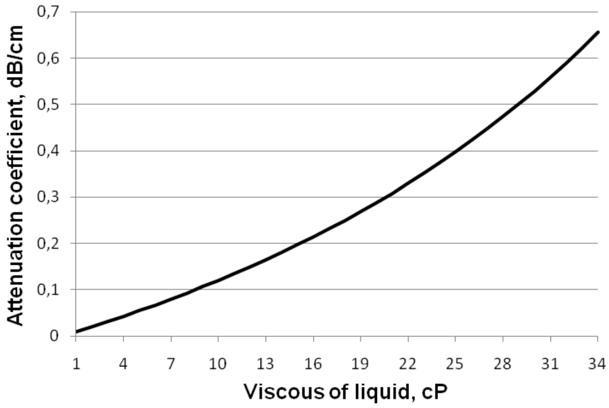



Fig. 3. Dependence of averaged absorption coefficient on viscosity at the frequency of 22 kHz, if the density of liquid is 1000 kg/m$^3$ and sound velocity is 1500 m/s

Dependence of absorption coefficient (Fig. 3) is presented taking into consideration the presence of "developed" cavitation in liquid. Calculated values of the absorption coefficient in cavitating medium are 0.1…0.7 dB/cm. It is necessary to compare these results with the values of absorption coefficient without cavitation. For this purpose results of measurements of ultrasound absorption presented in the paper [9] are used. The measurements were carried out at low intensities of influence at high megahertz frequencies, that excluded the generation of cavitation pockets. The results of experimental studies [9] let calculate that, for example, in olive oil at the frequency of 22 kHz attenuation coefficient is no more than 0.0057 dB/cm. This value is essentially small in comparison with damping decrement in cavitating liquid.

On the base of known values of absorption coefficient amplitude distribution of fluctuations of medium pressure at different longitudinal sizes of the cylindrical technological volumes was found (Fig. 4).

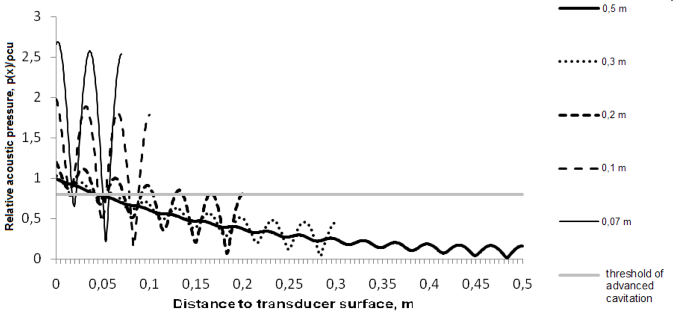



Fig. 4 – Dependence of acoustic pressure on the distance to the surface of the transducer at different longitudinal sizes of the technological volumes for low-viscous epoxy resin (ED-5)

In Fig. 4 threshold of acoustic pressure corresponding to the mode of "developed" cavitation is marked with bright line. Fig. 4 shows, that at the processing of epoxy resin ED-5 in the technological volume with large longitudinal size 0.5 m the size of advanced cavitation zone is no more than 0.05 m or 5 cm. It is evidence of possibility of processing in such volume of small amount of liquid, that is not suitable for practical ultrasonic cavitation processing of viscous liquids. At the decrease of longitudinal size of the technological volume due to reflective effects the amplitude of acoustic pressure in several zones increases. So if the size of the technological volume is 0.2 m, there is advanced cavitation zone (in which the amplitude of pressure is higher than the threshold of advanced cavitation) in the area lying in the distance of 0.1 m from the surface of the transducer. Inspite of essential fall of acoustic pressure in standing-wave node (evidently expressed minimums in the dependences given in Fig.4) owing to the processes of mixing uniform processing of liquid in the area near the surface of the transducer having expanded size 0.1 m is provided. At this size of the volume in 0.1 m there is no fraction of unprocessed liquid. Further downsizing of processed volume does not lead to increase of efficiency of processing as amount of liquid in the volume is less than the area of cavitation zone defined earlier, i.e. there are optimum longitudinal size of the technological vessel. Table I shows the results of combined optimization of the sizes of the technological volume and intensities of influence.

TABLE I
THE OPTIMIZATION OF THE SIZES OF THE TECHNOLOGICAL VOLUME AND INTENSITIES OF INFLUENCE

| Liquid | Intensity, W/cm$^2$ | Size of the cavitation zone in traveling wave, cm | Optimum size of the cavitation zone, cm | Optimum intensity, W/cm$^2$ |
|---|---|---|---|---|
| Water | 10…12 | 15 | 34 | 9 |
| Oil | 10…12 | 8 | 23 | 17 |
| Epoxy resin ED-20 | 30…40 | 2 | 6 | 37 |

Obtained results let conclude, that limit of longitudinal sizes of processed technological volume leads to more even distribution of "advanced" cavitation zones in comparison with larger volumes, where entered energy is mostly located near the surface of the transducer.

## VI. CONCLUSION

In the article mathematical of the process of cavitation zone generation consisting of plenty of bubbles in limited in size cylindrical technological volume was designed.

The results of theoretical investigations showed dominating influence of cavitation bubbles on ultrasound absorption in processed medium, which essentially exceeds the values obtained in non-cavitating viscous liquid medium. Mechanisms of cavitation influence on absorption of ultrasonic wave such as wave scattering on bubbles and the work spent for extension of the cavitation pockets are studied.

It is ascertained that owing to abnormal high damping of the acoustic wave limiting generation of cavitation zone existing equipment does not suit for ultrasonic cavitation processing of viscous liquids.

It was shown the possibility to increase the efficiency of ultrasonic cavitation processing of high-viscous and fine-dispersed liquids due to the use of special technological volumes with reflective walls for providing the standing wave mode.

## REFERENCES

[1] Khmelev, V.N. Increase of effectiveness of ultrasonic processing viscous and dispersive liquid mediums [Text] / V.N. Khmelev, S.S. Khmelev, R.N. Golykh // Polzunovsky Journal №3. – Barnaul: AltSTU, 2010. – P. 321-325. in Russian
[2] Khmelev, V.N. Ultrasonic Multifunctional and Specialized Equipment for Intensification of Technological Processes in Industry [Text] / V.N.Khmelev, G.V. Leonov, R.V. Barsukov, S.N. Tsyganok, A.V. Shalunov. – AltSTU, BTI. – Biysk: Publishing house of AltSTU, 2007. – 414 p. in Russian
[3] Khmelev, V.N. Ultrasonic Multifunctional and Specialized Equipment and their application in conditions of small industry, agriculture and household [Text] / V.N. Khmelev, O.V. Popova. – Barnaul: AltSTU, 1997. – 160 p. in Russian
[4] Novickiy, B.G. Application of acoustic oscillations in chemical-technological processes [Text] / B.G. Novickiy. – M.: Chemistry, 1983. – 192 p. in Russian
[5] Rozenberg, L.D. Powerful ultrasonic fields [Text] / L. D. Rozenberg. – M: Science, 1968. – 265 p. in Russian
[6] Minnaert, M. On musical air-bubbles and the sounds of running water [Text] / M. Minnaert // Philosophical Magazine vol. 16, 1933. – P. 235-248. in Russian
[7] Rozhdestvenskiy, V. V. Cavitation [Text] / V. V. Rozhdestvenskiy. – Leningrad: Судостроение, 1977. – 248 p. in Russian
[8] Krasilnikov, V.A. Introduction into physical acoustic [Text] / V.A. Krasilnikov, V.V. Krylov. – M.: Science, 1984. – 403 p. in Russian
[9] Mikhajlov, I.G. Attenuation of ultrasonic waves in liquids [Text] / I.G. Mikhajlov, S.B. Gurevich // Successes of physical sciences. Vol. XXXV, issue 1. – M.: Physical Institute after P.N. Lebedev RAS, 1948. – 35 p. in Russian

**Roman N. Golyh (S'10)** was born in Kazan, Russia in 1990. In this time he is student of Biysk Technological Institute. IEEE Student Member since 2010. Research areas of interest are ultrasonic equipment and technologies, mathematical modeling of technological processes under the influence of ultrasonic oscillations in various mediums.

**Vladimir N. Khmelev (**SM'04)—pro-rector at Biysk technological institute, professor, Full Doctor of Science (ultrasound). Honored inventor of Russia. Laureate of Russian Government premium for achievements in science and engineering. Area of scientific interests is application of ultrasound for an intensification of technological processes. IEEE member since 2000, IEEE Senior Member since 2004. His biography published in 7th issue of book "Who is who in scientific and engineering"

**Sergey S. Khmelev** was born in Prokopievsk, Russia, 1985. Now hi is student of Biysk Technological Institute. His research interests is design and construction ultrasonic oscillation system.