Evaluation of Optimum Modes and Conditions Providing Increasing Ultrasonic Cavitation Area in High-Viscous and Non-Newtonian Fluids

Roman GOLYKH
Biysk Technological Institute (branch) of the Altay State Technical University, Biysk, grn@bti.secna.ru

Andrey SHALUNOV
Biysk Technological Institute (branch) of the Altay State Technical University, Biysk, shalunov@bti.secna.ru

Vladimir KHMELEV
Biysk Technological Institute (branch) of the Altay State Technical University, Biysk, vnh@bti.secna.ru

Roman LOPATIN
Biysk Technological Institute (branch) of the Altay State Technical University, Biysk, Exsecrabilis01@yandex.ru

Vyacheslav MINAKOV
Biysk Technological Institute (branch) of the Altay State Technical University, Biysk, slava2926@mail.ru

Vladislav SHAKURA
Biysk Technological Institute (branch) of the Altay State Technical University, Biysk, shakura.va@bti.secna.ru

Abstract: - The aim of this work is improving the efficiency of chemical technology processes implemented in high viscosity or non-Newtonian fluids by evaluating modes and conditions of ultrasonic action, which provide an increase in the volume of the formed cavitation area. As a result of the research, a theoretical model of cavitation area formation in the non-Newtonian medium has been developed. The analysis of the model allows to calculate the optimal intensity of ultrasonic action (for linear-viscous fluids, the optimal intensity ranges from 1.6 to 80 W/cm^2; for nonlinear-viscous fluids up to 120 W/cm^2) and the distance (60-125 cm) between the irradiating surface and the reflecting boundary providing the maximum cavitation area volume. Last stage of presented studies the model was confirmed experimentally.

Keywords: - Ultrasound, Cavitation, Cavitation bubbles, High viscous medium, Non-Newtonian fluid

1. INTRODUCTION

At present day the improvement of the approaches and the methods of the solution of different technological tasks of the chemical industry remains is actual. Much attention is paid to the processes in the systems with the fluid phase. The necessity of modification of the physical-chemical structures of various media requires searching new and developing existing methods of the action. One of the promising methods of action is the application of ultrasonic vibrations. High efficiency of ultrasonic is proved by many studies for different technological media with fluid phase [1–8]. Ultrasonic allows increasing efficiency of the processes in these mediums. However, the most part of modern ultrasonic equipment lets carrying out chemical engineering processes (in industrial scales) only in the medium with the viscosity of up to 200 mPa·s even with using multi-zone radiators [9].

Existing ultrasonic equipment does not allow to realize processes in high-viscous (viscosity is more than 200 mPa·s) or non-Newtonian fluids in industrial scales. It is caused by the following reasons:

1) limiting of intensity (no more than 10 W/cm^2) and the radiating surface (no more than 15 cm^2);

2) limiting of active processed cavitation zone (size in all dimensions is less than 5 cm), which is determined by diffraction divergence and the absorption of ultrasonic vibrations in the cavitation medium and also high threshold values of intensities

of the ultrasonic action required for the cavitation appearance.

Thus, the aim of the paper is to increase the efficiency of the processes of the chemical technologies realized in the high-viscous or non-Newtonian fluids. The efficiency must be increased by determination of ultrasonic influence modes (intensity) and conditions (technological volume geometry), which provide increasing of the volume of formed cavitation area.

The determination of ultrasonic influence modes and conditions, which provide increasing of the volume of formed cavitation area, is **main goal** of the paper.

To achieve stated goal following particular tasks are formulated:

1. To develop theoretical model of the formation of the cavitation area in the high viscous and non-Newtonian fluids based on complex study of the cavitation area taking into account the effects and the phenomena occurring inside the area and allowing determine the form and sizes of the cavitation zones in fluid medium at different modes of the cavitation development.

2. To experimentally confirm the theoretical conditions and the modes of the cavitation area generation.

Further, the developed theoretical model, which describes the generation of the cavitation area in the high viscous and non-Newtonian fluids, is given.

2. THEORETICAL RESEARCH

It is necessary to develop theoretical model of the generation and the evolution of the cavitation zones under the action of ultrasonic vibrations. The ultrasonic vibrations are formed by the solid-state radiator. The developed model has three levels of details:

1. *The lower level* includes the analysis of the single bubble dynamics depending on the properties of carrying fluid phase. The analysis determines the dependence of the cavitation bubble radius R on the time t, the intensity of ultrasonic vibrations I and the rheological properties of fluid Λ (the initial viscosity μ_0 (Pa·s), the consistency K (Pa·s^{N+1}) and the non-linearity N indexes).

2. *The middle level* includes the analysis of the cavitation bubbles ensemble in the area with specific sizes L, which are less than the length of the ultrasonic wave λ, but more than the radius of the cavitation bubble R ($\lambda >> L >> R$).

In the frames of the middle level of the model the specific power of the shock waves in the unit of volume of the cavitation zone, the wave impedance and the absorption coefficient are determined. The total power of generated shock waves, absorption coefficient is evaluated in dependency on ultrasonic intensity and rheological properties of fluid. Evaluated maximum value of the total power of generated shock waves will be used as a measure of efficiency of the cavitation action.

3. *The top level*. In the top level of the model consideration scaling of obtained results for all processed volume of the fluid is carried out.

It allows determining the intensity of ultrasonic action and defining the size and the form of the technological tank (for specified geometry of the ultrasonic radiator), which provide generation of the cavitation zone with the largest volume.

Further in the second subsection the lower and the middle levels of details of the model are considered [10].

2.1. The lower level of details

At the lower level of details of the model the functional dependence of the cavitation bubble radius on time is determined on the base of equation of the single bubble dynamics for the stage of expansion taking into account non-Newtonian properties of fluid [10] and known Kirkwood-Bethe equation for the stage of the collapse [11].

The lower level of details of the model allows determining acceptable range of the intensities, in which cavitation is possible to carry out ultrasonic action depending on the initial viscosity, the consistency index K and the non-linearity N of fluid. According to the calculations, the range cannot exceed 100 W/cm^2. However, the cavitation power at boundary intensities of the range is zero. At the zero cavitation power the processes requiring cavitation cannot be realized.

Obviously, the intensity between boundary intensities of the range providing maximum cavitation power exists. To determine the intensity, it is necessary to study the generation of the ensemble of the cavitation bubbles. This study is realized within the frames of the middle level of details of the model.

2.2. The middle level of details

At the middle level of the model the ensemble of the cavitation bubbles is analyzed. The ensemble is considered in the area with the specified sizes L. The sizes are less than the length of the ultrasonic wave λ, but are much larger than the radius of the cavitation bubble R: $\lambda >> L >> R$.

It allows determining the dependences of the number concentration and the volume content of the cavitation bubbles (cavitation index) on the intensity of ultrasonic vibrations I, the time t and the rheological properties of fluid $\mathbf{\Lambda}$.

The number concentration of the bubbles is defined on the base of the analysis of the kinetic equation of disintegration and convergence of the bubbles [10, 11]. Further on the base of the number concentration n_{bub} (m^{-3}) and the volume content $\overline{\delta_1}$ of the bubbles the specific power of the shock waves (P_s) in the unit of volume of the cavitation zone, the wave resistance of cavitating fluid (ρc) and in finish the absorption coefficient (K_*) are defined:

$$K_* = -\frac{\omega}{c_0}\operatorname{Im}\frac{\rho_0 c_0^2 \overline{\delta_1}}{\left(\sqrt{2\rho c I}\right)e^{i\varphi}};\; I = \frac{\left|\overline{p_1}\right|^2}{2\rho c};\; \overline{\delta_1} = \frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} \delta(t)e^{-i\omega t}dt;$$

where I is the intensity of ultrasonic vibrations, W/m^2; ρ is the density of the cavitating medium, kg/m^3; c is the sound velocity in the cavitating medium, m/s; φ is the phase shift of the sound pressure $\overline{p_1}$, rad; t is the time, s; ρ_0 is the density of fluid phase, kg/m^3; c_0 is the sound velocity in fluid phase, m/s; ω is the circular frequency of ultrasonic vibrations, s^{-1}; $\delta(t)$ is the instantaneous value of the volume content of the bubbles in fluid.

Value of the absorption coefficient will be the measure of the efficiency of the cavitation action. The coefficient is power of shock waves divided by ultrasonic intensity.

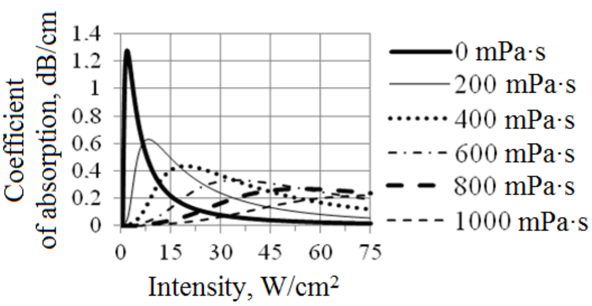

Figure 1. The absorption coefficient dependences on ultrasonic intensity for linear-viscous fluids

The dependences of the absorption coefficient on the ultrasonic intensity for the fluid with different rheological properties are shown in Figure 1. The dependences of the absorption coefficient have extremes. The extremes positions define optimum intensities (Figure 2) providing maximum of absorption coefficient and consequently maximum efficiency of cavitation influence in local area.

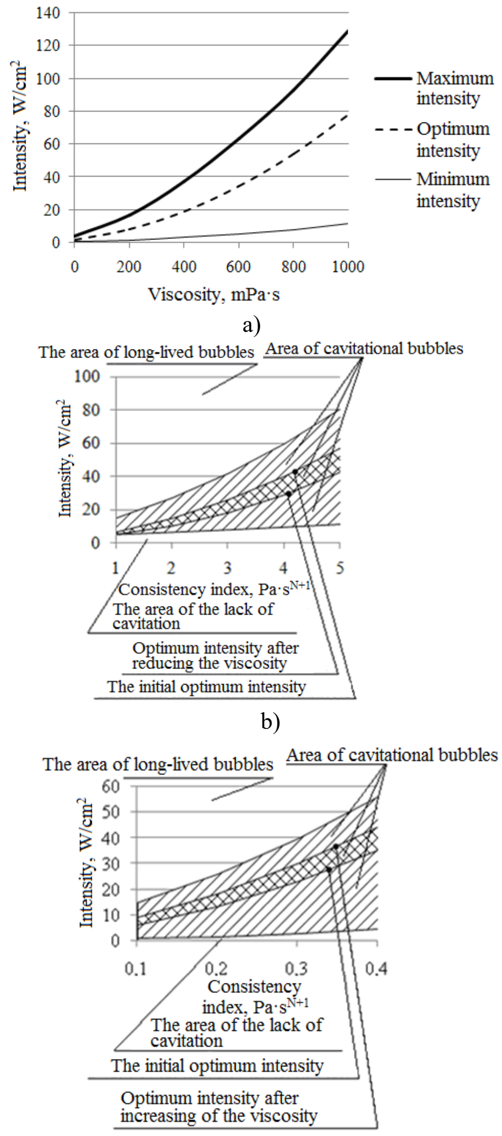

Figure 2. The dependences of the optimal and boundary intensities on the consistency index of linear-viscous (a) and non-Newtonian fluids: pseudoplastic (N = -0.1) (b) and dilatant (N = 0.1) (c)

Presented results can be the base for the analysis of the generation of the cavitation zones in the technological chambers and the determination of the optimum conditions of the action.

2.3. The top level of details

Further it is necessary to determine optimum conditions of ultrasonic action to maximize the volume of generated cavitation zone. The determination of the optimum conditions of ultrasonic action is carried out within the frames of the analysis of the high level of details of the theoretical model of the generation of the cavitation zone. The high level is based on the wave equation for the intensity of ultrasonic vibrations in the cavitating medium:

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

where I is the intensity of ultrasonic vibrations, W/m^2; φ is the phase shift of the vibrations of sound pressure in the medium; ω is the circular frequency of the initial ultrasonic field, s^{-1}; c_0 is the sound velocity in a continuous fluid, m/s; ρ_0 is the density of fluid phase, kg/m^3; ρ is the density of the cavitating medium, kg/m^3; c is the sound velocity in the cavitating medium, m/s; $\overline{\delta_1}$ is the complex amplitude of the change of the volume content of the cavitation bubbles relatively to the mean value.

The equation was solved by iteration method:

$$\Delta\left(p_{\mathrm{Re}}{}^{(k+1)}+ip_{\mathrm{Im}}{}^{(k+1)}\right)+\frac{\omega^2}{c_0^{\,2}}\times\left(p_{\mathrm{Re}}{}^{(k+1)}+ip_{\mathrm{Im}}{}^{(k+1)}\right)=$$

$$=\frac{\omega^2}{c_0^{\,2}}\rho_0 c_0^{\,2}\overline{\delta_1}\left(p_{\mathrm{Re}}{}^{(k)}+ip_{\mathrm{Im}}{}^{(k)}\right)$$

where $\lim\limits_{k\to\infty}\left(p_{\mathrm{Re}}{}^{(k)}(\mathbf{x})+ip_{\mathrm{Im}}{}^{(k)}(\mathbf{x})\right)=\sqrt{\rho c I(\mathbf{x})}e^{i\varphi(\mathbf{x})}$.

The distribution of intensity of the ultrasonic vibrations defined on the base of the equation (1) at specified geometry of the ultrasonic radiator and the technological tank allows determining the distribution of the cavitation zones corresponding to the following modes:

- *the mode of absence of the cavitation*, at which the collapse of the bubbles does not occur and the intensity of ultrasonic action is less than the threshold value I_1 determined on the base of the analysis of the lower level of the model (see Figures 2a–c) (zones);

- *the mode of incipient cavitation* ($I_1 \le I \le I_2$), in which the collapse of the bubbles occurs with low amplitudes of the pressure of the shock waves (less than $20\cdot10^5$ Pa), and the acceleration of physical-chemical processes in the medium under the action of ultrasound is very small (zones);

- *the mode of developed cavitation* ($I_2 \le I \le I_3$), in which the collapse of the bubbles occurs with maximum amplitudes of pressure of the shock waves ($20\cdot10^5 \ldots 80\cdot10^5$ Pa); at that physical-chemical processes in the fluids influenced under the action of ultrasonic vibrations proceed the most efficiently; the criterion of the mode of developed cavitation (determining the borders of the intensities range I_2 and I_3) in the total power of shock waves

$$\frac{\int_0^T 4\pi R^2(t)\,n_{bub}P_{sh}^{\,2}(t)\,dt}{\rho_0 c_0 T}\ge P_{crit},$$

where R is instantaneous radius of cavitation bubble, m; n_{bub} is cavitation bubbles concentration, m^{-3}; $P_{sh}(t)$ is shock wave pressure in bubble interior, Pa; c_0 is the sound velocity in a continuous fluid, m/s; ρ_0 is the density of fluid phase, kg/m^3; T is period of ultrasonic oscillations, s; P_{crit} is critical specific power of shock waves, at which the aluminium foil (thickness 9 μm) is destructed by cavitation during 2 min, W/m^3.

The P_{crit} is determined by experimentally. The calorimetric method was used for determining P_{crit}, because without chemical reactions $P_{crit}=\frac{Q_{\min}}{V}\approx\frac{cm\Delta T_{\min}}{V}$, where c is specific heat capacity, J/(kg·K); m is mass of fluid, kg; V is volume if fluid, m^3; ΔT_{min} is fluid temperature change during ultrasonic treatment, K; Q_{min} is minimum heat at which the foil is destructed during 2 min, J (zones);

the mode of degenerating cavitation ($I_3 \le I \le I_4$), in which the intensity of the bubble collapse is decreased in comparison with the mode of developed cavitation, and the bubbles as a rule make radial vibrations without collapsing during 2 periods of the initial ultrasonic waves and more from the moment of the initial expansion (zones);

the mode of degenerated cavitation ($I > I_4$, where I_4 is determined from the dependences shown in Figures 2a–c), in which the collapse of bubbles is absent, and they make radial vibrations in the neighborhood of the mean radius (zones).

Figures 3a–c show the forms and the positions of the cavitation zones in the symmetry plane of the ultrasonic radiator for different intensities of ultrasonic action in the unlimited volume without reflectors. The cavitation zones are corresponding to five modes of the cavitation mentioned above. The viscosity of the model fluid is 100 mPa·s, the model ultrasonic radiator is of piston type (the diameter of the working tool is 40 mm). As it follows from presented Figures 3a–c, with the growth of the action intensity the length of the zone of developed cavitation increases along the acoustic axis of the radiator. However, beginning with 16.25 W/cm^2 for model fluid the rise of the zone of developed cavitation does not occur. That is why, it is necessary to create the conditions for optimum distribution of ultrasonic pressure, for instance, by the design of operating tanks with the reflecting surfaces (Figures 3d–e). As it follows from Figures 3d–e at the presence of the reflecting wall the zone of developed cavitation increases in the volume up to 1.4 times due to the summation of the incident and the reflecting waves.

It is evident, that there is an optimum distance, at which the volume of the zone of developed cavitation will be maximum. The presence of the optimum distance can be explained by the fact, that at small distances between the radiator and the reflecting wall the total volume of the processed fluid is small, and at the large distances the zone of developed cavitation is concentrated near the radiating surface (Figures 3b–c).

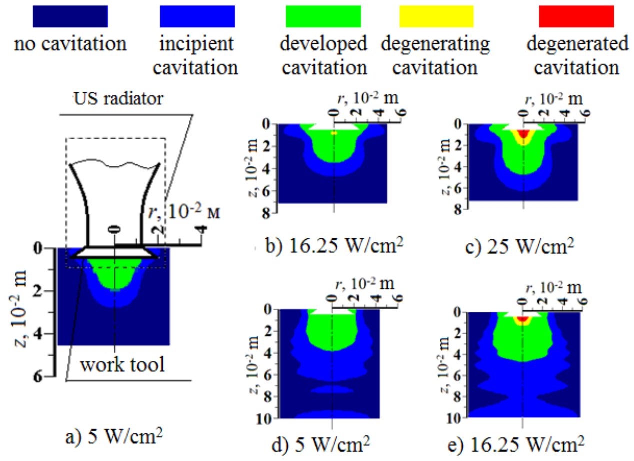

Figure 3. The distributions of the cavitation zones

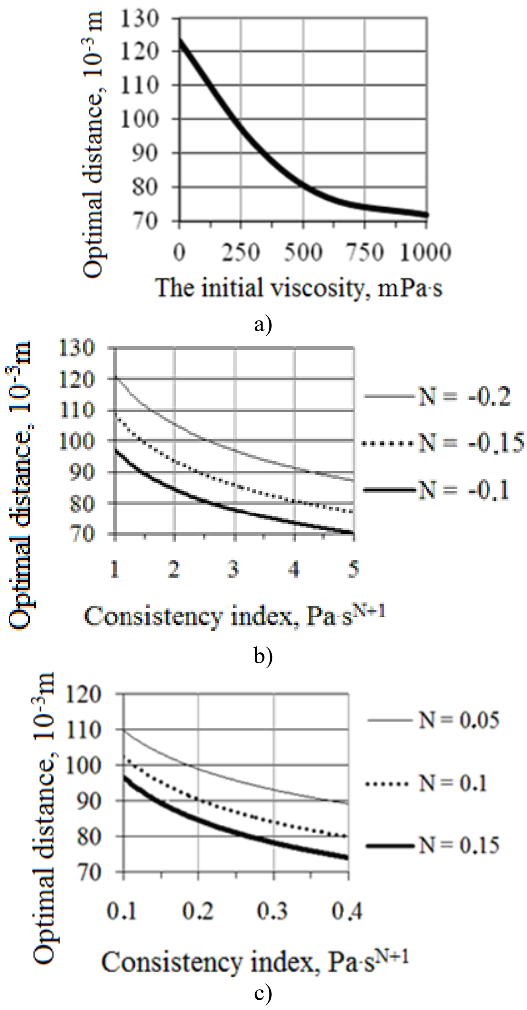

Figure 4. The dependences of the optimal distance between the radiating surface and the reflecting boundary on fluids rheological properties: a) linearly viscous; b) dilatant; c) pseudo plastic

The concentration of the zone of developed cavitation near the radiating surface is caused by high absorption coefficient of ultrasonic waves in cavitating medium with fluid phase exceeding 20 dB/m. Figures 4a–c show the dependences of the optimum distance on the rheological properties of fluid phase.

However, all useful volume to be processed (in which there is a developed cavitation) lies between the radiator and the reflecting surface and it does not exceed 0.08 l in the case of the classic piston radiator. Such value of the volume proves insufficient efficiency of the piston working tools for the industrial application.

2.4. Multi-zone radiators

For the increase of total volume of the zone of developed cavitation it is necessary to use the radiators with increased surface of the radiation. The use of the multi-zone radiator (with the length of 400 mm and the diameters of the waveguide parts of 70/45 mm; radiating area of this is 250 cm^2) in the cylinder chamber (with the diameter of 208 mm) without internal reflectors allows achieving the volume of the zones of developed cavitation of 3.92 l for the model medium with non-Newtonian fluid phase (the consistency index is 0.2 Pa·s^{N+1}, the nonlinearity is 0.15), as at the application of the working tools of the piston type this volume does not exceed 0.08 l.

However, the degree of uniformity of the ultrasonic processing in the cylinder tank without internal reflectors is very low for the industrial use (the portion of the volume of developed cavitation zone does not exceed 35 % of the total volume of 12.61 l).

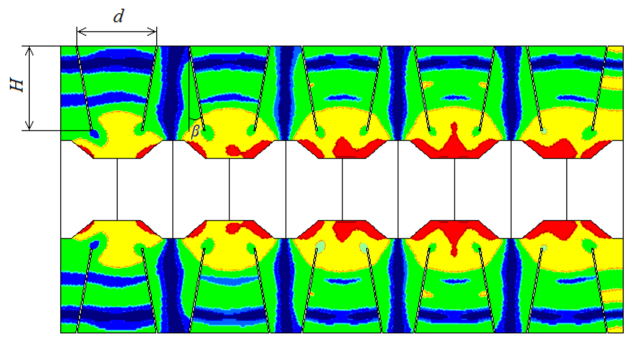

Figure 5. The distributions of the cavitation zones in longitudinal section of a process tank with the ring plate reflectors

Further analysis of the distributions of the cavitation zones in the technological tanks of various geometries allows determining, that the construction with the ring plate reflectors (Figure 5) containing the holes of the small diameter (3…6 mm) is the most efficient in comparison with the length of ultrasonic wave in the cavitating fluid.

In such construction the volume of developed cavitation zone increases up to 5.8 l (46 % of the total volume) at the optimization of the geometric parameters of the plate reflectors by the method of gradient descent.

The method of gradient descent includes following steps:

1. At the first stage the choice of the initial values of the parameters is realized, namely: d is the distance between the projections and H (Figure 5) is the height of the projection (for instance, d = 50 mm, H = 50 mm), the stop criterion $\varepsilon = 0.001$ l/mm, the value of the gradient step Γ = 0.05 mm^2/l.

2. Further the distribution of the amplitude of the sound pressure $P(\mathbf{x})$ is calculated for current values of the parameters d, H.

3. It is calculated the value of the function of the volume of developed cavitation zone (m^3)

$$V_{cav}(d,H) = \int_{\Omega(d,H)} \theta(P(d,H,\boldsymbol{x}) - P_2)\theta(P_3 - P(d,H,\boldsymbol{x}))dV;$$

where $P(d,H,\mathbf{x})$ is the distribution of sound pressure, Pa, at the specified parameters d (m), H (m).

4. The functions of the volume of developed cavitation zone depending on the distribution of sound pressure is calculated:

$$V_{cav}(d+\Delta x, H) = \int_{\Omega(d+\Delta x,H)} \theta(P(d+\Delta x, H, \mathbf{x}) - P_2)\theta(P_3 - P(d+\Delta x, H, \mathbf{x}))dV;$$

where Δx = 0.5 mm.

5. The module of function gradient V is calculated, and it is compared with required accuracy:

$$\Delta R = \frac{1}{\Delta x}\left|\begin{pmatrix} V_{cav}(d+\Delta x, H) - V_{cav}(d,H) \\ V_{cav}(d, H+\Delta x) - V_{cav}(d,H) \end{pmatrix}\right|.$$

If $\Delta R < \varepsilon$, then the calculation stops.

6. The parameters d and H are changed in a following way:

$$\begin{pmatrix} d \\ H \end{pmatrix} \rightarrow \begin{pmatrix} d \\ H \end{pmatrix} - \frac{\Gamma}{\Delta x}\begin{pmatrix} V_{cav}(d+\Delta x, H) - V_{cav}(d,H) \\ V_{cav}(d, H+\Delta x) - V_{cav}(d,H) \end{pmatrix}.$$

7. Go to step 2.

For the realization of the optimization algorithm the computer program was developed.

The absolute maximum volume of developed cavitation zone is achieved at d = 36 mm and H = 70 mm, i.e. when reflecting projections totally cover the cross-section of a fluid flow.

It should be mentioned, that at such construction the volume of developed cavitation zone exceeds in 2-3 times the volume achieved in a simple cylinder of the optional (non-optimum) diameter.

Thus, the theoretical model of the generation of cavitation zone allows studying the influence of the conditions of propagation and reflection of ultrasonic vibrations (the size and the form of the technological tank) on the total volume occupied by the zone of the most efficient cavitation action, which determines the productivity of processing.

The analysis of the high level of details of the theoretical model lets:

– defining optimum distances between the reflecting border and the radiator providing the increase of the volume of the developed cavitation zone in no less than 50%; it is shown, that the optimum distances lie within the range of 50 to 125 cm and they decrease at the growth of viscosity of processed medium;

– determining, that the most efficient construction of the technological tank is a free-flowing technological chamber with the ring plate reflectors (Figure 6) allowing the increase of volume of the developed cavitation zone up to 3 times.

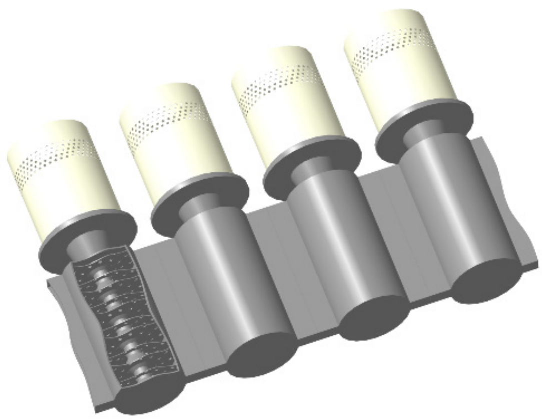

Figure 6. The multistage flow reactor design with the annular reflectors

Further the results of the experimental studies aimed at the proof of the adequacy of developed models are given.

3. THE RESULTS OF THE EXPERIMENTS

At the first stage the experimental studies determined the dependence of the volume of the developed cavitation zone on the intensity of ultrasonic action by the definition of the size of the area of cavitation erosion of metal foil submersed into fluid under the action of ultrasonic vibrations. Equivalent viscosity of fluid is 100 mPa·s, the ultrasonic radiator is the piezoelectric element of the piston type with the diameter of the working tool of 40 mm, and the duration of action is 2 min.

a) 60 mm (6.71 %) b) 90 mm (8.09 %) c) 130 mm (6.22 %)

Figure 7. The distributions of the zones of developed cavitation at various distances between the radiator and the reflecting boundary

The photos of the zones of the cavitation erosion of the aluminum foil (thickness is 9 μm) at different intensities of action are shown and at different distances between the radiating surface and the reflecting border are shown in Figures 7a-c (the values of the fraction volumes of zones of developed cavitation are in brackets; the intensity of action is 7.5 W/cm^2).

Obtained experimental dependences of the fraction of the volume of processed fluid occupied by the developed cavitation zone on the distance between the radiating surface and the reflecting border for different media by the viscosity of fluid are given in Figure 8.

The experimental values of maximum achieved fraction of the volume occupied by the developed cavitation zone and the optimum distances between the radiator and the reflecting surface for different rheological properties of fluid are shown in Table 1. The analysis of presented data allows confirming adequacy of proposed theoretical model, as the relative error does not exceed 20%. Also, the results of the experiments prove the possibility of the increase of the fraction of the volume of developed cavitation zone in 1.5 times (for instance, for epoxy resin ED-20) by the optimization of the distance between the radiator and the reflecting border at unchanged intensity of action.

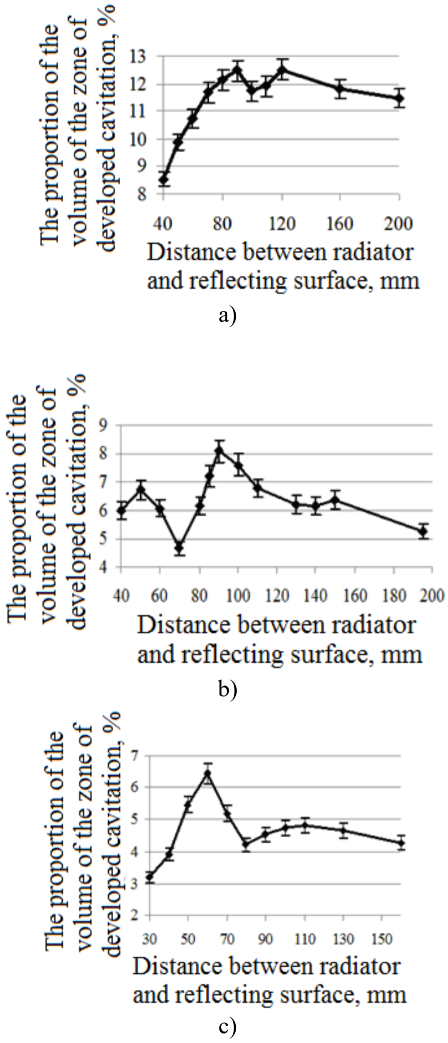

Figure 8. The dependences of the volume fraction of developed cavitation zone on the distance between the radiator and the reflecting boundary: a) in water (the intensity is 3 W/cm^2); b) in oil (the intensity is 7.5 /cm^2); c) in epoxy resin ED-20 (the intensity is 25 W/cm^2)

Table 1. Experimental values of the fractions of the volumes of the developed cavitation zone and the optimum distance between the radiator and the reflecting surface

Name of fluid	Experimental values of the fraction of fluid volume occupied by the developed cavitation zone, %		Values of the optimum distances between the radiating surface and the reflecting border		
	At the optimum distance between the radiator and the reflector	Without reflector	Theoretical, L_T, 10^{-3} m	Experimental, L_E, 10^{-3} m	Relative error, $\lvert L_T - L_E \rvert \cdot 100/L_E$, %
Water	12.51514	11.44543	123	120	2.5
Sunflower oil	8.08803	5.254	102	90	13.3
Epoxy resin ED-20	6.442366	3.190952	71	60	18.3

4. CONCLUSIONS

It was developed the theoretical model of the generation of the cavitation zone in non-Newtonian medium, on the base of which analysis it was determined optimum intensities of ultrasonic action providing the most power of the shock waves.

On the base of developed model optimum intensities of the ultrasonic action and the distance between the radiating surface and the reflecting border providing maximum power of the cavitation were determined.

For instance, for the linear viscous fluids the optimum intensities were from 1.6 to 80 W/cm^2; for non-linear-viscous fluids were up to 20 W/cm^2.

It was defined the optimum distances between the radiating surface and the reflecting border, which range was 60–125 cm. The providing of these distances allowed increasing the volume of the developed cavitation zone in more than 50%.

Carried out theoretical studies were proved experimentally.

ACKNOWLEDGMENTS

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