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Evaluation of ultrasonic influence intensities providing formation of cavitation area in liquids with various rheological properties

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ABSTRACT: *The model of cavitation area containing cavitation bubbles ensemble in high-viscous and non-Newtonian (usually with a solid dispersed phase) liquids is presented in this article. Proposed model is based on the study of the cavitation bubbles ensemble as a whole but taking into account the main effects and phenomena occurring inside this ensemble. This model takes into account coalescence and breakup of bubbles due to collapsing. According to model, breakup and coalescence effects lead to concentration bubbles dependency on ultrasonic pressure amplitude or intensity. Thus, these effects affect on total energy of shock waves being generated by collapsing cavitation bubbles as well as bubble radius. The analysis of the model allows revealing optimum intensities of the ultrasonic influence, that are necessary to provide maximum total shock wave energy, at which, for example, the maximum degree of solid particle's destruction (maximum interphase surface contact) or maximum free surface "liquid-gas" due to formation and breakage of capillary waves (formed on liquid's free surface) is achieved. The analysis of the model lets evaluating, that optimum intensity of the influence for the most of liquids does not exceed 40 W/cm*^{2} *at the frequency of 22 kHz. However for dilatant liquids intensity of influence can achieve 100 W/cm*^{2}*. Obtained results can be applied for the choice of power modes of the ultrasonic technological equipment to increase interphase surface under cavitation influence.*

KEYWORDS: *Cavitation, coalescence, dispersing, ultrasonic, viscosity*

I. INTRODUCTION

One of promising approach to increase interphase contact surface in systems "liquid-solid particles" and "liquid-gas" is an ultrasonic cavitation influence on liquid or liquid-dispersed media. This influence implements ultrasonic dispersing of solid particles in liquids or formation of capillary waves on liquid's free surface bounding between liquid and gas. The uniqueness and efficiency of the ultrasonic influence on liquid or liquid-dispersed media is determined by the formation of cavitation gas-and-steam bubbles, which accumulate energy at their extension during one of half-period of vibrations and generate shock waves and cumulative jets at their collapse during the other half-period of vibrations [1-3]. Cavitation influence helps to change structure and properties of substance and materials, increase interphase surface of the interaction in liquid-dispersed systems or surface "liquid-gas", realize the processes of dissolution, extraction, emulsification, etc.

However, most liquid-dispersed mediums are high-viscous or non-newtonian. Cavitation ultrasonic treatment of such media in practice cannot be realized owing to a number of reasons which are absence of scientific data on the influence of the modes, at which maximum total energy of shock waves causing dispersing of suspensions is achieved; necessity of high intensity of ultrasonic influence (more than 25 W/cm^2) to advance cavitation with maximum total energy of shock waves in high-viscous and non-linear viscous liquid-dispersed media. Stated problems do not allow designing ultrasonic equipment providing the productivity of ultrasonic cavitation dispersing (increasing of interphase surface between liquid and solid) in high-viscous and non-Newtonian liquid media, which is sufficient for industrial applications.

II. PROBLEM STATEMENT

To determine the modes of ultrasonic influence providing the formation of the cavitation area in processed liquids different in their properties it is necessary to develop the model, which takes into account both all the main effects and phenomena occurring inside the area, and allows analyzing cavitation area containing cavitation bubbles ensemble as a whole. The problem became more complicated, as in the most part of theoretical papers [3-6] directed to the development of scientific foundation of efficiency increase of ultrasonic cavitation treatment of liquid or liquid-dispersed media it is considered the behaviour of single bubble in liquids, which viscosity does not depend on deformation rate (rate of shear). However, obtained results of studies cannot be applied to high-viscous and non-newtonian media, as they do not take into account following important factors:

[1] nonlinear character of the dependence of viscous stress forces on fluid velocity gradient preventing from the extension of cavitation pocket;
[2] changes of mean viscosity of processed medium after a time due to the influence of the processes of mixing and viscosity hysteresis leading to the decrease of threshold intensity, which is necessary for occurring of cavitation shock waves causing dispersing of solid particles.

Moreover the efficiency of cavitation influence defined by total shockwave energy of cavitation bubbles depends not only on the behaviour of single bubbles but also on the concentration of bubbles. This concentration due to the interaction of cavitation bubbles changes with a time and depends on the intensity of ultrasonic effect, that is proved by the results of the experimental studies carried out before.

Thus, complex studies of the process of the cavitation area formation should include:

[1] study of the behavior of single bubble to determine permissible regimes of the influence, at which collapse of cavitation bubble occurs and it does not degenerate into long-lived one. At that for the first time the presence of the dependence of liquid viscosity on the rate of shear and the relaxation of the viscosity as a result of the cycle of radial expansion and collapse of cavitation bubble are taken into consideration;
[2] study of the behavior of all bubbles ensemble taking into account their interaction, which determine energy characteristics of the area as a whole, and revealing of optimum modes of the interaction, at which total energy of bubble collapse is maximum. At this stage new approach based on revealing of stationary concentration of cavitation bubbles as a result of their breaking up and coalescence and determining of ultrasonic absorption coefficient in cavitating medium caused by expenditure of energy on the formation of cavitation can be used [7].

III. ANALYSIS OF THE DYNAMICS OF SINGLE BUBBLE FOR THE EVALUATION OF ALLOWABLE RANGE OF THE INTENSITIES OF ULTRASONIC EFFECT

The analysis of the dynamics of single bubble subject to the properties of liquid is in definition of functional dependence of cavitation bubble radius R on time *t*, amplitude of acoustic pressure *p* and rheological properties of liquid **P**:

$$R = f\left(t, p, \mathbf{P}\right).$$

Required functional dependence is defined on the base of the analysis of obtained equation of the dynamics of single bubble taking into account the dependence of liquid viscosity on the rate of shear:

$$R\frac{\partial^2 R}{\partial t^2} + \frac{3}{2}\left(\frac{\partial R}{\partial t}\right)^2 = \frac{p(R) - p_\infty}{\rho} + \frac{R^2 \frac{\partial R}{\partial t}}{\rho}\int_R^\infty \frac{1}{r^3}\frac{\partial \varphi}{\partial r}\left(\sqrt{I_2}\right)\partial r \qquad (1)$$

where *R* is the instantaneous radius of the cavitation bubble, m; *p(R)* is the liquid pressure near the walls of the cavitation bubble, Pa; p_∞ is the instantaneous value of the acoustic pressure, Pa; $\sqrt{I_2}$ is the Euclidean norm of deformation rate tensor, s^{-1}; φ is the certain function defined the dependence of liquid viscosity μ on rate of shear, Pa·s, at that $\mu = \frac{\varphi\left(\sqrt{I_2}\right)}{2}$; *r* is distance from bubble center, m.

Euclidean norm of deformation rate tensor is

$$\sqrt{I_2} = \sqrt{\sum_{i,j=1}^{3}\left(\frac{\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}}{2}\right)^2} = \sqrt{\left(R^2\frac{\partial R}{\partial t}\right)^2 \frac{6}{r^6}}$$

where u_i (for $i = 1 \ldots 3$) are liquid velocity projections to Cartesian axes.

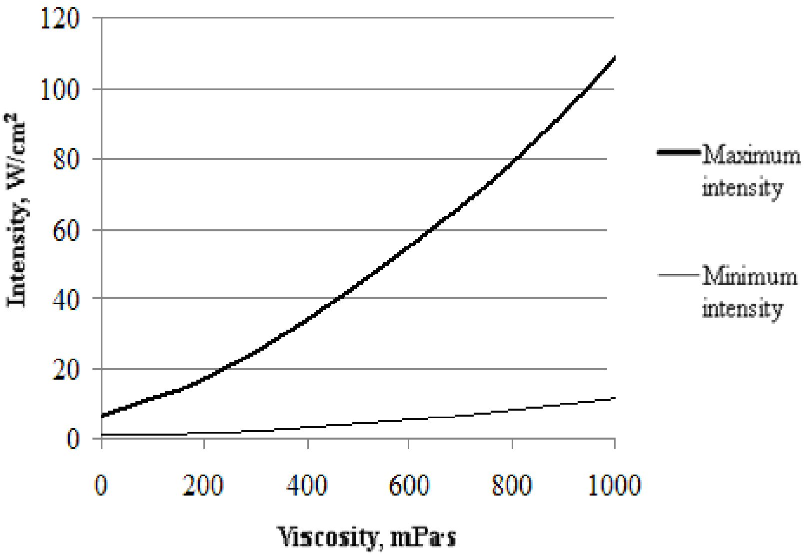
Equation (1) is obtained as a result of integration of the momentum conservation equation in differential form in the volume of liquid flowing around the cavitation bubble. Integrated equation of momentum conservation takes into consideration the presence of arbitrary dependence of the liquid viscosity on the rate of shear, which is Euclidean norm of the deformation rate tensor $\sqrt{I_2}$.

The function φ is defined by three parameters characterizing rheological properties of liquids: starting viscosity μ (Pa·s), consistency index K (Pa·s^{N+1}) and nonlinearity index N.

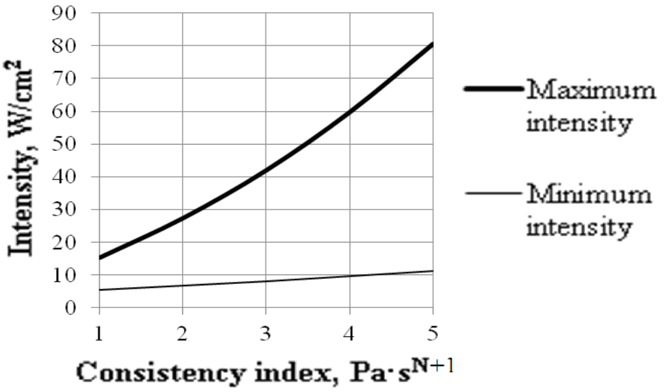
$$\phi\left(\sqrt{I_2}\right)=2\mu\left(1+\left(\frac{K}{2\mu}\right)^{\operatorname{sgn} N}\left(\sqrt{I_2}\right)^{|N|}\right)^{\operatorname{sgn} N}$$

This function was obtained by experimental data for liquid and liquid-dispersed mediums with different concentrations of solid particles.

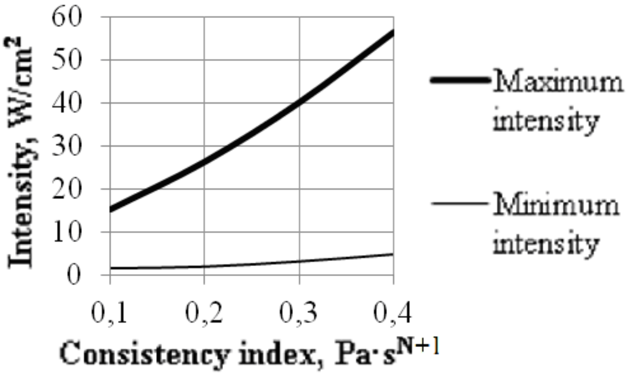
As it is known, that surface tension of liquid lightly influences on the maximum radius of the bubble, it is possible not to take it into account at the analysis of the formation of cavitation area, it equals to 0.072 N/m, [1-3]. The density of the most liquids varies in the narrow range (900…1200 kg/m^3) and it does not influence greatly on the cavitation process. Therefore high emphasis is placed on the studies of the influence of rheological properties of liquid on optimum action modes. At that depending on the rheological properties of liquids they are divided into *linear-viscous* (the viscosity does not depend on the rate of shear), *pseudoplastic* (the viscosity decreases with the growth of the rate of shear) and *dilatant* (the viscosity increases with the growth of the rate of shear). Generally, dilatant liquids are suspensions with high-concentration (more than 30%) of solid particles. Obtained results are given for all three types of liquids. The analysis of the dynamics of single bubble allows determining of permissible range of intensities, in which it is necessary to realize ultrasonic influence depending on starting viscosity, consistency index K and nonlinearity index N of the liquids (see Fig.1).



a) linear-viscous



b) pseudoplastic (nonlinearity index N=-0.1, starting viscosity – 1 Pa·s)



c) dilatant (nonlinearity index N = 0.15, starting viscosity 0.1 Pa·s)

Fig. 1. Dependencies of boundary intensities of influence on rheological properties of liquids

At minimum intensities determined by these dependences cavitation only begins to originate (the speed of bubble collapse achieves speed of sound in pure liquids), at maximum intensities bubble collapse does not occur (the absence of collapse during 3 periods of initial ultrasonic wave and more from the moment of initial expansion of the bubble). As it follows from presented dependences, the range of possible intensities can exceed 100 W/cm^2.Thus, theoretical analysis of the dynamics of the single bubble is insufficient for determination of optimum modes and conditions of the influence, as at boundary intensities the energy of shockwaves generated by the aggregates of bubbles is close to zero and consequently the efficiency of treatment will be insignificant.
It is evident, that in this range there is narrower range of optimum intensities, at which efficiency of cavitation causing dispersing of solid particles will be maximum. To determine this range of intensities it is necessary to study the formation of ensemble of cavitation bubbles, as the energy of cavitation influence is defined by total energy of shockwaves generated by each single cavitation bubble.

IV. ANALYSIS OF THE FORMATION OF BUBBLE ENSEMBLE FOR THE DEFINITION OF OPTIMUM INTENSITIES OF ULTRASONIC INFLUENCE

The analysis of cavitation bubbles ensemble is carried out in the range with characteristic dimensions *L*, which is much less than the length of the ultrasonic wave λ, but much more than the radius of the cavitation bubble *R*:

$$\lambda >> L >> R$$

It helps to define the dependence of the concentration $n(m^{-3})$ of the cavitation bubbles on the amplitude of acoustic pressure, time and rheological properties of the liquid **P**.

The dependences of the concentration of cavitation bubbles are determined on the base of the equation of the kinetics of breaking and coalescence of the bubbles given in [8]:

$$\frac{\partial n}{\partial t} = \frac{n(j-1)}{iT_0} - k_B n^2 \qquad (2)$$

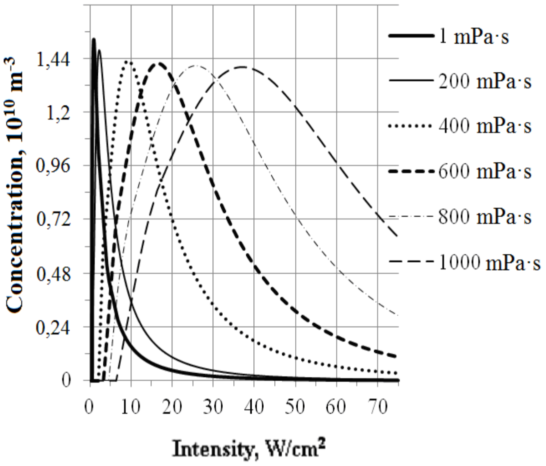
where n is concentration of cavitation bubbles being depended on time t(s), m^{-3}; i is average count of cavitation bubble oscillations before its breakup; k_B is coalescence rate, м^3/с; T_0 is ultrasonic oscillations period, s; j is average number of nuclei formed after breakup of alone bubble.
Coalescence rate is defined by following expression:

$$k_B = \frac{S_{eff}\langle u\rangle}{2}$$

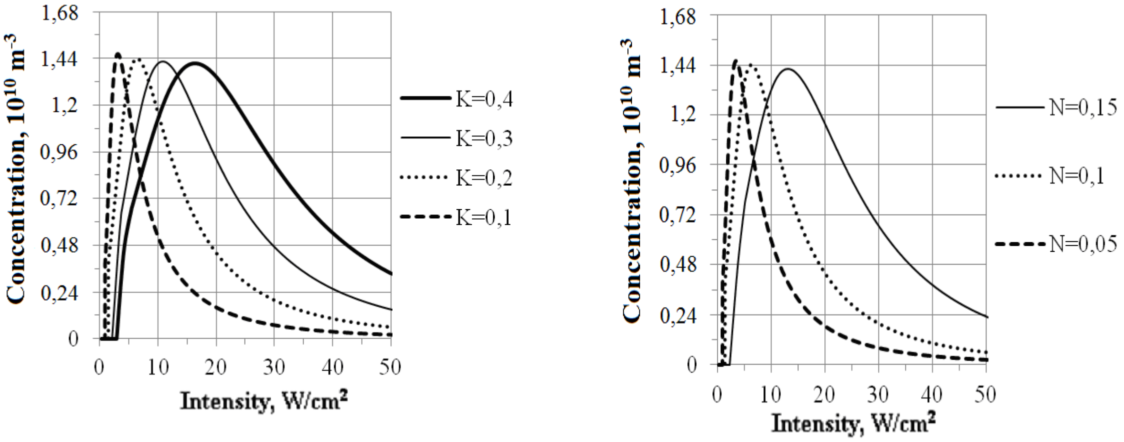
where S_{eff} is square of effective collision cross-section which is $S_{eff}=25\pi R_{MAX}^2$ (R$_{MAX}$ is maximum bubble radius, m), m^2; <*u*> is average velocity of bubbles proximity, m/s.

<*u*> is defined by differential equations of bubbles motion given in [4].

Average number of nuclei (*j*) formed after breakup of alone bubble is defined by experimental data given in [3].Obtained bubbles concentration dependences on intensity and rheological properties of the liquid are shown in Fig. 2.

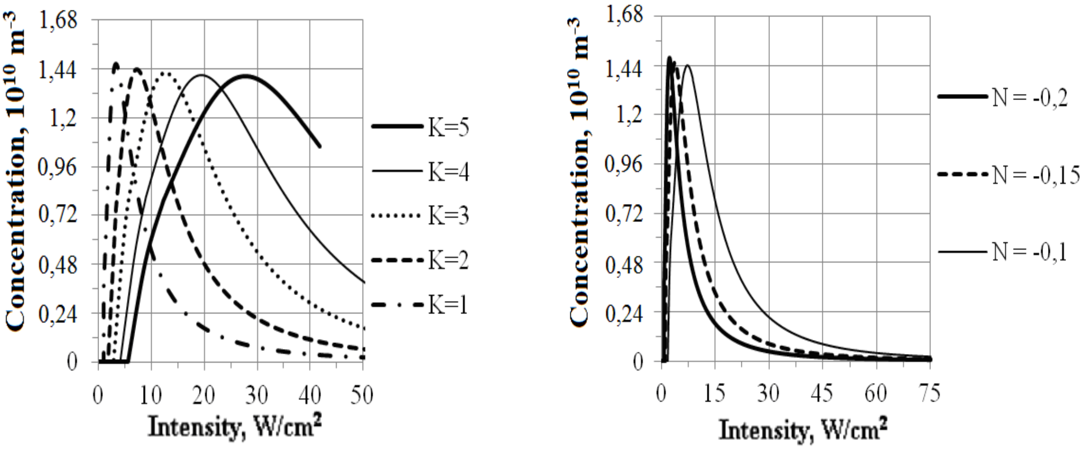


a) linear-viscous liquids



b) pseudoplastic with different consistency indices K, Pa·s^{N+1} (nonlinearity index N = 0.1, starting viscosity is 0.1 Pa·s)

c) pseudoplastic with different nonlinearity indices N (consistency index K = 0.2 Pa·s^{N+1}, starting viscosity is 0.1 Pa·s)



d) dilatant with different consistency indices K, Pa·s^{N+1} (nonlinearity index N = -0.1, starting viscosity is 1 Pa·s)

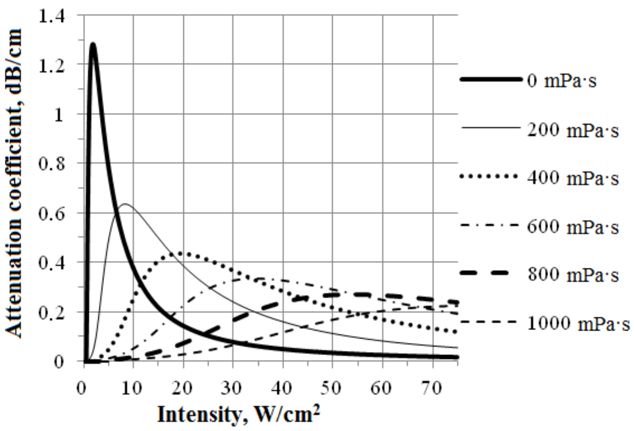
e) dilatant with different nonlinearity indices N (consistency index K = 2 Pa·s^{N+1}, starting viscosity is 1 Pa·s)

Fig. 2. Dependences of bubbles concentration on the intensity of influence for the liquids with different rheological properties

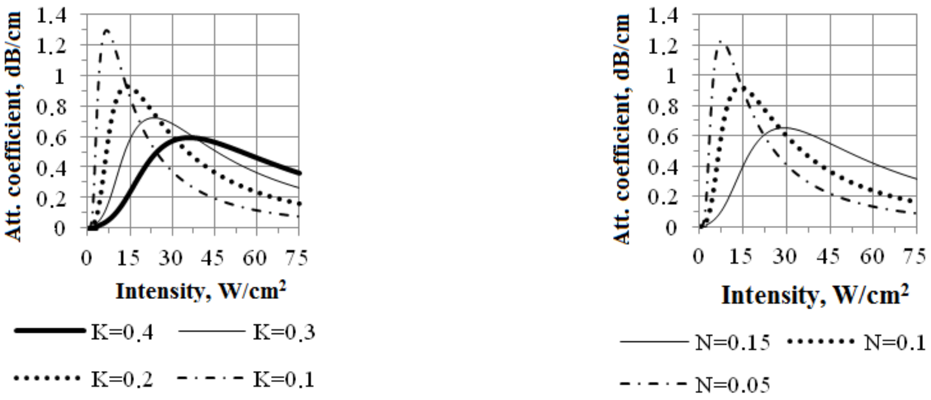
These dependences were used for further definition absorption coefficient, which is in proportion to the total energy of shock waves and it is a measure of the efficiency of cavitation influence [9].At that the absorption coefficient in cavitating liquid is defined on the base of following obtained expression:

$$K_* = -\frac{\omega}{c_0}\operatorname{Im}\frac{\rho_0 c_0^{2}}{\overline{p_1}}\,\frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}}\frac{4}{3}\pi R^3(t)\,n e^{-i\omega t}\partial t$$

where $\overline{p_1}$ is complex amplitude of the 1st harmonics of the pressure (Pa), ω is the vibration frequency of the acoustic radiator in liquid medium, s^{-1}, ρ_0 is the steady-state density of liquid phase, kg/m^3, c_0 is the velocity of sound in pure liquid, m/sec; *n* is previously determined bubbles concentration, m^{-3}; *R(t)* is bubble momentum radius determined equation (1) for alone bubble dynamics. The dependences of the absorption coefficient on intensity of influence for the liquids with different rheological properties are given in Fig. 3.

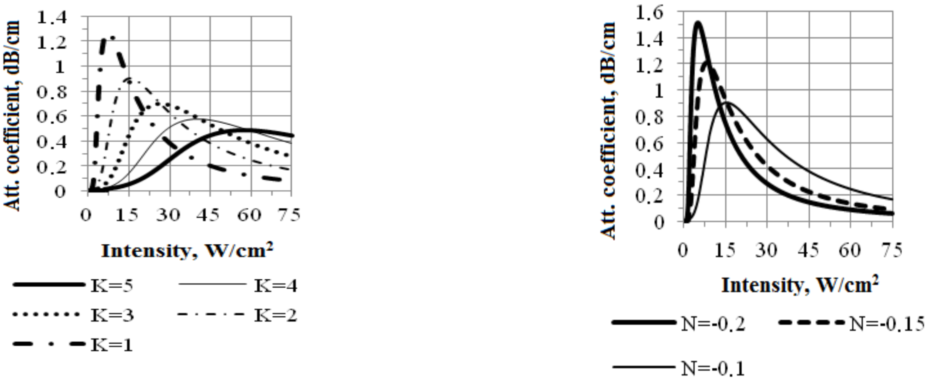


a) linear-viscous



b) pseudoplastic with different consistency indices K, Pa·s^{N+1} (nonlinearity index N = 0.1, starting viscosity is 0.1 Pa·s)

c) pseudoplastic with different nonlinearity indices N (consistency index K = 0.2 Pa·s^{N+1}, starting viscosity is 0.1 Pa·s)



d) dilatant with different consistency indices K, Pa·s^{N+1} (nonlinearity index N = -0.1, starting viscosity is 1 Pa·s)

e) dilatant with different nonlinearity indices N (consistency index K = 2 Pa·s^{N+1}, starting viscosity is 1 Pa·s)

Fig. 3. Dependences of absorption coefficient on the intensity of influence for the liquids with different rheological properties

The dependence of the absorption coefficient on the intensity of influence has extreme character and maximum position determines optimum intensity of ultrasonic influence, as in this case maximum degree of energy transformation of initial ultrasonic wave into the energy of shock waves generated by cavitation bubbles is achieved. Thus, at optimum intensity maximum efficiency of ultrasonic cavitation influence is achieved. Dependences of minimum, maximum and optimum intensities of influence for linear-viscous liquids are shown in Fig.4.

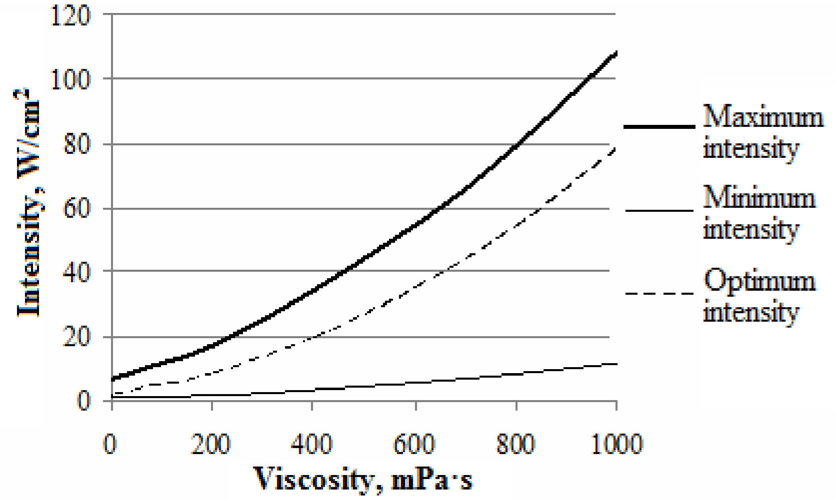
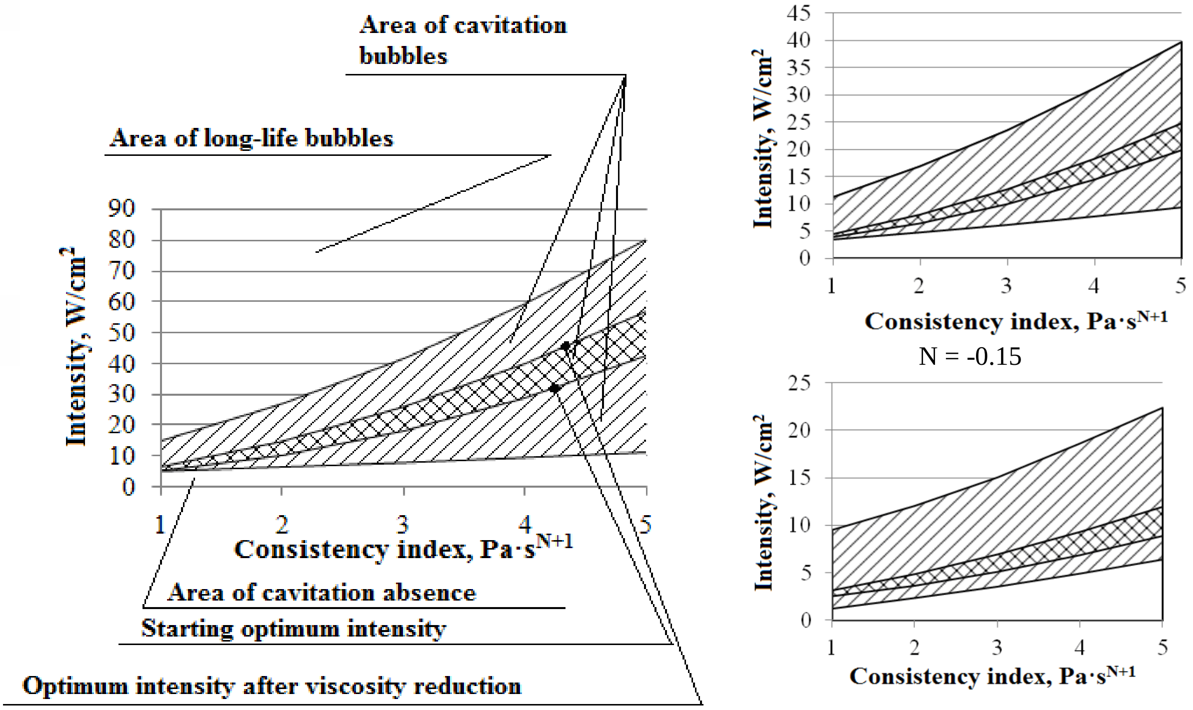


Fig. 4. Dependences of maximum, minimum and optimum intensities of influence for linear-viscous liquids

It should be noted, that in the case of nonlinear-viscous liquids the dependence of optimum intensity on the parameters characterizing their rheological properties lies in the certain range. It can be caused by the changes of their rheological properties due to the viscosity relaxation during the processing. The dependences of the range of optimum intensities for non-Newtonian liquids are shown in Fig. 5, 6. In Fig. 5 dependences for pseudoplastic liquids are shown.



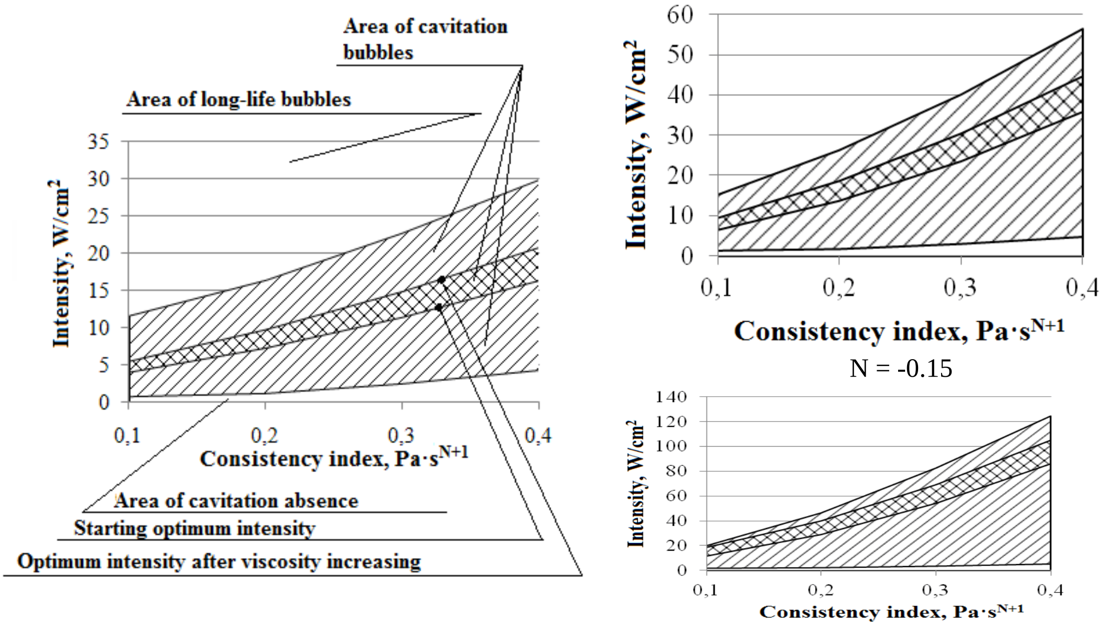
N = -0.15

N = -0.1

N = -0.2

Fig. 5. Dependences of boundary intensities of influence on rheological properties of pseudoplastic liquids with different non-linearity indices

In Fig. 6 dependences for dilatant liquids are shown.



N = -0.15

N = -0.1

N = -0.2

Fig. 6. Dependences of boundary intensities of influence on rheological properties of dilatant liquids with different non-linearity indices

As it follows from Fig.5 during the processing optimum intensity decreases in 5…20 W/cm^2 for pseudoplastic liquids, while for dilatant liquids (Fig. 6) intensity increases in 5…15 W/cm^2 due to the rise of their viscosity under the influence of ultrasound. It causes the necessity of adjustment of output power of the ultrasonic apparaus during the processing.

Table I shows the values of optimum intensities of influence and optimum amplitudes of radiator's vibrations for different liquids used in practice. The values given in the table were obtained with the application of the dependences presented in Fig.4-6.

Table I. The values of optimum intensities of influence for the liquids used in practice

Name of liquid	Starting viscosity, Pa·s	K, Pa·s^{N+1}	N	Optimum intensity, W/cm^2	Optimum amplitude, μm
Water	0.00082	0	0	1.73	0.7
Olive oil	0.085	0	0	4.51	1.7
Motor oil PMS-400	0.4	0	0	19.25	7.4
Glycerin	0.6	0	0	34.4	13.3
Epoxy resin ED-5	3	5	-0.15	19.95…24.77	7.7…9.6
Trifunctional oligoestercyclocarbonates on the base of propylene oxide	4	5	-0.2	11.92…23.4	4.6…9.03
Water-coal suspension (mass concentration 20%)	0.1	0.1	0.1	13.74…18.74	5.3…7.2

Presented results can be directly used for the choice of power operation modes of the ultrasonic equipment at known rheological properties of processed liquid or and liquid-dispersed medium.

V. CONCLUSION

During carried out researches for the first time we proposed the approach for the determination of optimum modes of ultrasonic influence based on the formation of cavitation area as a whole. At that developed model of the formation of cavitation area takes into consideration the main effects and phenomena occurring inside the area:

[1] coalescence of the bubbles at radial vibrations and breaking up at collapse;
[2] influence of the dependence of liquid viscosity on the rate of shear on the dynamics of the single bubble; viscosity relaxation of liquid with time under the action of cavitation.

It is shown that coalescence and breaking up of bubbles cause concentration bubbles dependency on ultrasonic intensity. This dependency may be explanation that optimum intensity at total collapse bubbles energy achieving maximum is exist. The analysis of the model allows revealing optimum intensities of ultrasonic influence, which is necessary for achieving of maximum total microscopic shock waves energy being generated in liquids with different rheological properties. It is determined, that optimum intensities of influence for the most of liquids used in practice do not exceed 40 W/cm^2. However, for dilatant liquids with the nonlinearity index of 0.15 and more the intensity of influence can achieve 100 W/cm^2. It is evident, that due to the viscosity relaxation the change of optimum intensity for non-newtonian liquids occurs in the course of time. The width of change range of the intensity achieves 20 W/cm^2. Obtained results can be applied for the definition of the intensity of ultrasonic influence providing maximum efficiency of liquid or liquid-dispersed medium treatment to increase interphase surface (for examples, dispersing of suspensions with solid particles or formation of capillary waves being broken into droplets on free surface "liquid-gas") with known rheological properties.

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