Determination of Ultrasonic Effect Mode Providing Formation of Cavitation Area In High-Viscous And Non-Newtonian Liquids

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Abstract – **The article presents the phenomenological model of the formation of cavitation area in high-viscous and non-Newtonian liquids. Proposed model is based on the study of the formation of cavitation area as a whole but taking into account the main effects and phenomena occurring inside this area. The analysis of the model allows revealing optimum intensities of the ultrasonic influence, which are necessary for the appearance of the mode of developed cavitation for liquids different in their rheological properties. The analysis of the model lets determining, that optimum intensities of the influence for the most of liquids does not exceed 40 W/cm^2 at the frequency of 22 kHz, with the exception of dilatant fluids, for which intensity of influence can achieve 100 W/cm^2. As a result of the model analysis it is found out the change of optimum intensity for non-Newtonian liquids with the course of time induced by the relaxation of viscosity. Increase or decrease of the intensity, which is necessary for the formation of cavitation area, achieves 20 W/cm^2. Obtained results can be applied for the choice of power modes of the ultrasonic technological equipment and the control of the process of cavitation treatment of media with different rheological properties.**

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

I. INTRODUCTION

ONE OF PROMISING approach to the solution of various technological tasks in modern productions is an ultrasonic cavitation influence on liquid and liquid-dispersed media. High efficiency and prospectivity of the ultrasonic influence are proved by many investigations for wide range of liquids (water, organic solvents, oils, petroleum, filled polymeric nanostructured materials, varnish-and-paint compositions, resins, concentrated suspensions of solid particles, etc.) [1]-[3].

The uniqueness and efficiency of the ultrasonic influence on liquid 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. Cavitation influence helps to change structure and properties of substance and materials, increase interphase surface of the interaction, realize the processes of dissolution, extraction, emulsification, etc.

At present cavitation treatment is successfully realized in practice and used in industry for the realization of the processes in low-viscous media (with the viscosity of up to 30 mPa•sec).

It is evident, that ultrasonic cavitation processing of media (oil, petroleum, polymers, etc.) of higher viscosity (up to 2 Pa•sec) and in some cases media, which viscosity depends on rate of shear, is also very important. Unfortunately, cavitation ultrasonic treatment of such media in practice cannot be realized owing to a number of reasons:

– absence of scientific data on the influence of the modes of ultrasonic effect on the process of formation of cavitation area in non-Newtonian media;

– necessity of high intensity of ultrasonic influence (more than 25 W/cm^2) to develop cavitation.

Stated problems do not allow designing ultrasonic equipment providing the productivity of ultrasonic cavitation treatment of high-viscous and non-Newtonian liquid media, which is sufficient for industrial application.

II. PROBLEM DEFINITION

To determine the modes of ultrasonic influence pro-viding the formation of the area of developed cavitation in processed liquids different in their properties it is necessary to develop the phenomenological model, which takes into account both all the main effects and phenomena occurring inside the area, and allows analyzing cavitation area 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 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.

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 [3].

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

– study of the behavior of single bubble, which is a “building brick” of the area 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;

– 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].

As according to the results of carried out researches ultrasonic influence is often realized in practice at the frequency of 22 kHz [1]-[3], further we determine energy parameters of influence at this frequency.

III. Analysis of the Dynamics of Single Bubble for the Determination 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**:

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

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:

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

where R is the instantaneous radius of the cavitation bubble, m, $p(R)$ is the liquid pressure near the walls of the cavitation bubble, Pascal, p_∞ is the instantaneous value of the acoustic pressure, Pascal, $\sqrt{I_2}$ 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 $\mu = \frac{\varphi\left(\sqrt{I_2}\right)}{2}$.

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 $\sqrt{I_2}$.

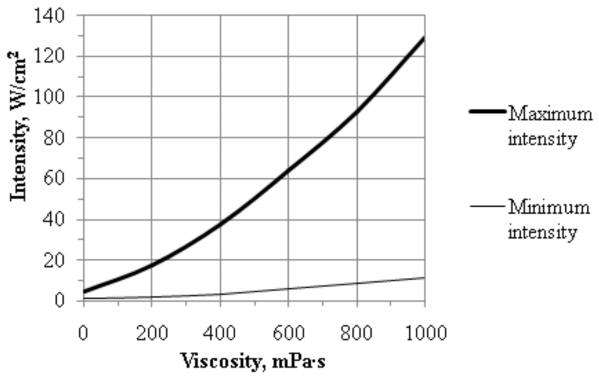
The function φ is defined by three parameters characterizing rheological properties of liquids: starting viscosity μ (Pa·s), consistency index K (Pa·s^N) and nonlinearity index N.

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.

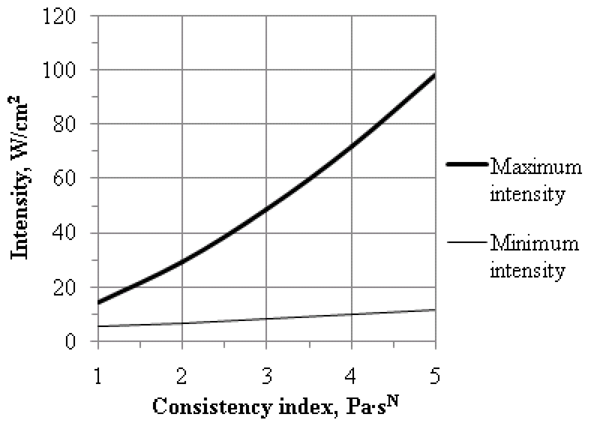
That is why; high emphasis is placed on the studies of the influence of rheological properties of liquid on optimum action modes.

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). Obtained results are given for all three types of liquids.

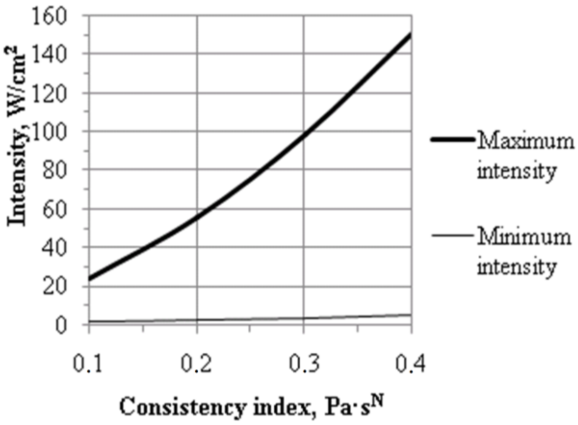
The analysis of the dynamics of single bubble allows determining of permissible range of intensities, in which it is necessary to realize ultrasonic influence depending on starting viscosity, consistency index K and nonlinearity index K of the liquids (see Fig.1).



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. Dependence 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 5 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 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 aggregate 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(м$^{-3}$)* and volume content δ of the cavitation bubbles (cavitation index) on the amplitude of acoustic pressure, time and rheological properties of the liquid **P**.

$$\delta(p,\mathbf{P}) = \frac{4}{3}\pi R^3 n(p,\mathbf{P})$$

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 obtained by Margules [8].

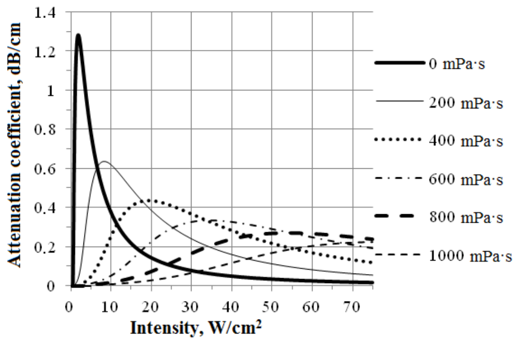
These dependences of volume content of cavitation bubbles on time are the base of further definition absorption coefficient, which is in proportion to the total energy of shock waves and it is a measure of the efficiency of cavitation influence [9].

At that the absorption coefficient in cavitating liquid is defined on the base of following obtained expression:

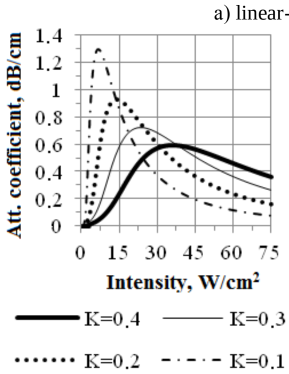
$$K_* = -\frac{\omega}{c_0}\,\mathrm{Im}\frac{\rho_0 c_0^{\,2}\,\overline{\delta_1}}{\overline{p_1}},$$

where $\overline{p_1}$ and $\overline{\delta_1}$ are complex amplitudes of the 1st harmonics of the pressure (Pa) and the volume content of the medium respectively, 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.

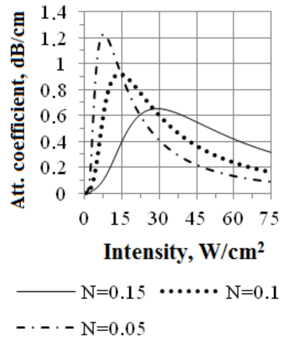
The dependences of the absorption coefficient on intensity of influence for the liquids with different rheological properties are given in Fig.2.



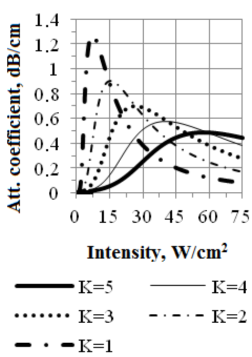
a) linear-viscous



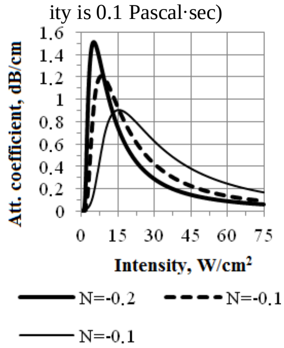
b) pseudoplastic with different consistency indices K (nonlinearity index N = 0.1, starting viscosity is 0.1 Pa·s)



c) pseudoplastic with different nonlinearity indices N (consistency index K = 0.2 Pa·s^N, starting viscosity is 0.1 Pascal·sec)



d) dilatant with different consistency indices K (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, starting viscosity is 1 Pa·s)

Fig. 2. 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.3.

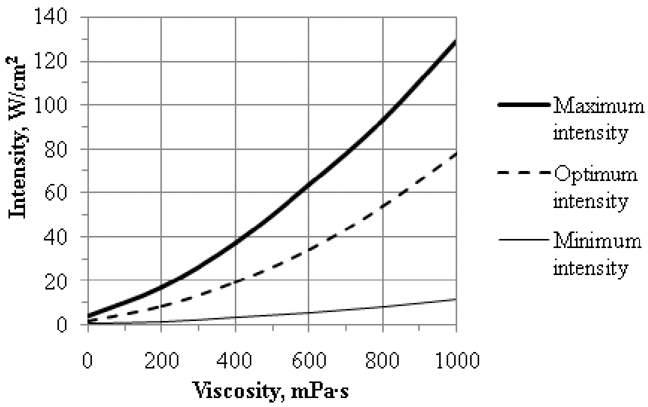
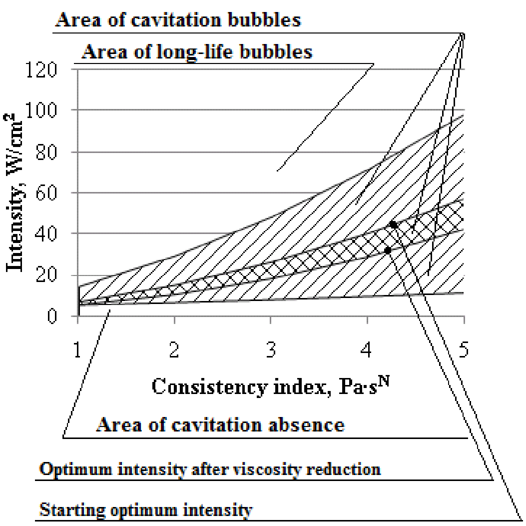
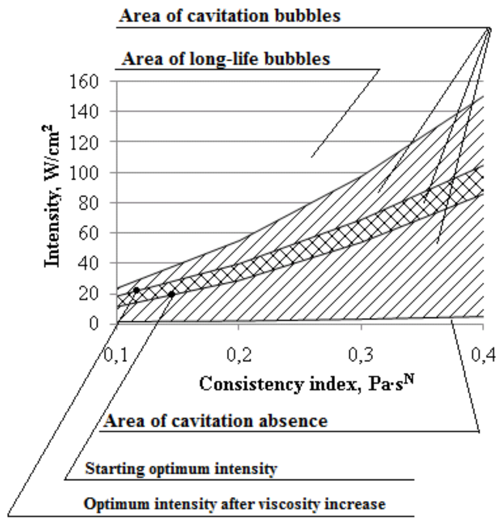


Fig. 3. Dependences of maximum, minimum and optimum intensities of influence for linear-viscous liquids

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.4.



a) for pseudoplastic liquids (nonlinearity index N = -0.1)



b) for dilatant liquids (nonlinearity index N = 0.1)

Fig. 4. Dependences of boundary intensities of influence on rheological properties of non-Newtonian liquids

As it follows from Fig.4 during the processing optimum intensity decreases in 5…20 W/cm^2 for pseudoplastic liquids, while for dilatant liquids inensity 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.

Tab. I shows the values of optimum intensities of influence for different liquids used in practice. The values given in the table were obtained with the application of the dependences presented in Fig.2.

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	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.

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 phenomenological model of the formation of cavitation area takes into consideration the main effects and phenomena occurring inside the area:

– coalescence of the bubbles at radial vibrations and breaking up at collapse;

– 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.

The analysis of the model allows revealing optimum intensities of ultrasonic influence, which is necessary for the formation of developed cavitation 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 treatment with known rheological properties.

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