Modes and Conditions of Efficient Ultrasonic Influence on High-Viscosity Media in the Technological Volumes

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***Abstract* – In the article the approach to efficiency increase of ultrasonic cavitation treatment of high-viscosity liquid media base on the optimization of the conditions of propagation of ultrasonic vibrations in cavitating liquid is proposed. Reveal of optimum conditions is realized on the base of the analysis of developed model of propagation and attenuation of ultrasonic waves in multibubble cavitating medium. The results of the optimization allow to develop the construction of specialized technological chamber of the ultrasonic flow reactor providing the increase of treatment efficiency in more than 50% due to the presence of reflecting plates.**

***Index Terms* – Ultrasound, cavitation, technological chamber, viscosity, composite polymer materials.**

I.INTRODUCTION

ULTRASONIC CAVITATION influence is a perspective method of modification of composite polymer materials (CPM). So in the paper [1] it is shown, that influence on epoxy resin ERO 1441-30 by ultrasonic vibrations with intensity of about 100 W/cm² during 5 minute leads to the decrease of its viscosity in 48%. It is also known, that introduction of different types of nanomodifiers [2] into resins increase ultimate strength of the articles made of CPM in more than 20% at bending and more than 30% in compression. The introduction of carbonic nanotubes by ultrasound [2] leads to the growth of ultimate strength of the articles in 72% in comparison with their introduction by the methods of mechanical agitation. It is evident and it was proved many times, that the efficiency of ultrasonic action is caused by cavitation processes in liquid media.

Unfortunately, ultrasonic technologies are not widely used at industrial production of polymer and composite materials. It can be explained by small area of radiation of vibrating systems applied in practice, difficulties of generation of high-intensity (more than 20...30 W/cm²) action for the realization of cavitation process in high-viscosity media, limitation of generated cavitation area due to abnormally high damping of ultrasonic vibrations in such media [3].

The construction of multi half-wave radiators [4] representing waveguides of cylindrical form of different diameter placed in series and in alignment lets solve the problem of multiple extension of radiation area.

Earlier the authors of the papers [3, 5] reaveled theoretically and experimentally the values of intensities, which were necessary and sufficient to achieve the mode of developed cavitation in liquid processed media different in physical properties. As a result of studies it was stated, that the main factor influencing on degree of cavitation development was viscosity. According to the results of theoretical and experimental researches for liquids with viscosity of upto 100 centipoise optimum intensity does not exceed 2...5 W/cm² and for liquids with viscosity of more than 400 centipoise it is more than 25 W/cm². To enter ultrasonic vibrations with intensity of more than 25 W/cm² into processed media at present multipacket piezoelectric transducers with power of more than 4 kW are developed and successfully applied [6].

However, further development and use of ultrasonic technologies is impossible without revealing the conditions, at which cavitation processes may be realized in maximum possible volumes of processed media.

It is caused the necessity of carrying out studies aimed at revealing of the conditions of generation and propagation of ultrasonic vibrations, which provide maximum size of the area of developed cavitation in different technological volumes for the realization of high productivity of ultrasonic processing of viscous media in practice.

II. PROBLEM DEFINITION

Final aim of present research is to determine optimum modes and conditions of ultrasonic action for the efficiency increase of the proceses of obtaining of highly filled nanostructured polymer and composite materials and control of their properties.

To achieve formulated aim it is necessary to solve following special tasks:

1) Reveal the reasons limiting the size of cavitation area in the media with high viscosity;
2) Determine the size of the zone of efficient cavitation influence in the volumes, which are not limited by reflecting walls;
3) Study the process of formation of cavitation areas in flowing technological volumes of cylindrical form limited by the sizes and reveal the conditions of maximum productivity of processing of technological media with high viscosity.

As practical realization of the revealing process of optimum modes of ultrasonic action and conditions of vibration propagation in cavitating liquid is characterized by labour expenditures because of necessity to use wide range of intensities of influence and construction of various technological volumes, we carry out theoretical researches with the application of mathematical model approach.

III. STUDY OF THE PROCESS OF FORMATION OF CAVITATION AREA

As it is mentioned above, at the first stage of the study it is necessary to determine the main reasons of sizeable attenuation of ultrasonic wave limiting the size of cavitation area. It is know, that at the realization of cavitation processed medium is a liquid rich in smallest steam-and-gas bubbles, that is why attenuation coefficient in such liquid is caused by energy loss for diffraction scattering and formation of shock waves at cavitation bubbles collapse. At that viscosity of liquid influences less on ultrasonic attenuation. So for instance, attenuation coefficient in olive oil caused by its viscosity does not exceed 0.0057 dB/cm. Thus conversion to cavitation mode leads to the increase attenuation coefficient of ultrasonic vibrations, and ultrasonic attenuation in formed cavitation area resists its extension.

To define the size of formed cavitation area depending on intensity of ultrasonic vibrations it is necessary to study in sequence the behaviour of single cavitation bubble in ultrasonic field and the propagation process of ultrasonic vibrations in cavitating liquid containing ensemble of cavitation bubbles with the purpose of definition of changes of their acostic properties depending on amplitude of acoustic pressure (vibration intensity).

The studies are carried out on the base of designed models taking into account influence of dependence of viscosity on rate of shear, which has most of polymer and composite materials. For that analysis of single cavitation bubble we assume, that most of non-linear viscous liquids are obeyed the power law of Ostwald-de Waele [7, 8] determining the dependence of viscosity on rate of shear for one-dimensional case (Couette flow):

$$\mu = \frac{K}{2}\left(\frac{\partial u}{\partial y}\right)^{\gamma} \tag{1}$$

where K is the consistency index of liquids, γ is the index of nonlinearity.

On the base of solution of Navier-Stokes system of equations [7] with the use of Olroyd [8] expression characterizing the dependence of viscosity on rate of shear for multidimensional case we obtain the equation of the dynamics of single cavitation bubble in liquid relative to its radius as a function on time:

$$\rho\left(\frac{3}{2}\dot{R}^{2} + R\ddot{R}\right) = p(R) - p_{\infty} + \int_{R}^{\infty} 6\dot{R}\gamma K R^{2\gamma+2}\left|\dot{R}\right|^{\gamma}\frac{6^{\frac{\gamma}{2}}}{r^{3\gamma+4}}\partial r = \tag{2}$$

$$= p(R) - p_{\infty} + \frac{2\dot{R}\gamma K}{\gamma+1}\left|\dot{R}\right|^{\gamma}\frac{6^{\frac{\gamma}{2}}}{R^{\gamma+1}}$$

where R is the instantaneous radius of the cavitation bubble, p(R) is the pressure of liquid near the walls of cavitation bubble, p_∞ is the instantaneous value of acoustiv pressure.

The equation lets to define instantaneous volume of cavitation bubble depending on the nonlinearity and consistency indices.

At next stage of the study we define the concentration of cavitation bubbles in local area of liquid, which sizes are much smaller than the sizes of generated cavitation area, but larger than the size of cavitation bubble. It is necessary for determining of acoustic properties of liquid-bubble medium generated during the cavitation process. To define concentration of cavitation bubbles in Margulis paper [9] the dependence of calculating concentration of cavitation bubbles on time was obtained:

$$n = \frac{n_{\infty} n_0}{n_0 + n_{\infty} e^{-n_{\infty} k_B t}}; \quad (3) \qquad n_{\infty} = \frac{j-1}{i k_B T_0} \quad (4)$$

where n_0 is the initial unknown concentration of cavitation bubbles, n_∞ is the steady concentration of cavitation bubbles defined by the expression (4), i is the average pulse number of the cavitation bubble before its collapse, k_B is the rate constant of coalescence of bubbles defined by the paper [9], T_0 is the duration of ultrasonic vibrations.

The equation for instantaneous radius of bubble and the expression for steady concentration of cavitation bubbles allow to determine their instantaneous volume content depending on generated acoustic pressure. The definition of volume content of steam-and-gas bubbles in liquid medium lets study the process of propagation of vibrations in the form of traveling or standing ultrasonic waves. It allows to estimate the size of area characterizing by developed cavitation and find out the conditions of formation of cavitation area of maximum size in different technological volumes.

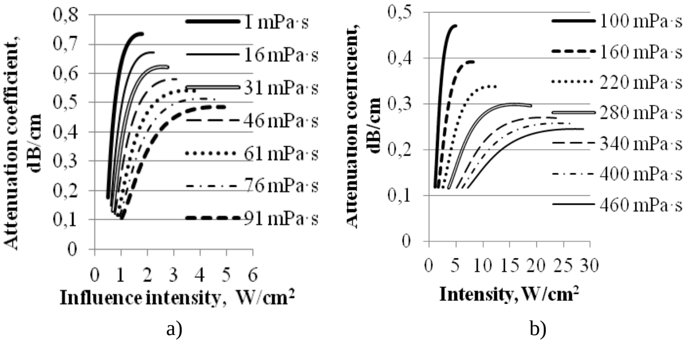
At neglect of higher harmonics wave equation for the 1st harmonics of pressure p_1 and volume content of bubbles δ_1 can be represented in a following way [10]:

$$\Delta\overline{p_1} + \frac{\omega^2}{{c_0}^2}\left(1 - \frac{\rho_0 {c_0}^2 \overline{\delta_1}}{\overline{p_1}}\right)\overline{p_1} = 0$$

At that effective attenuation coefficient is defined on the base of the following expression:

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

As viscosity is the main factor influencing on the degree of cavitation development in liquid medium, Fig.1 shows calculated dependences of attenuation coefficient in cavitating linear-viscous liquids on intensity of ultrasound for different in viscosity liquids [2].

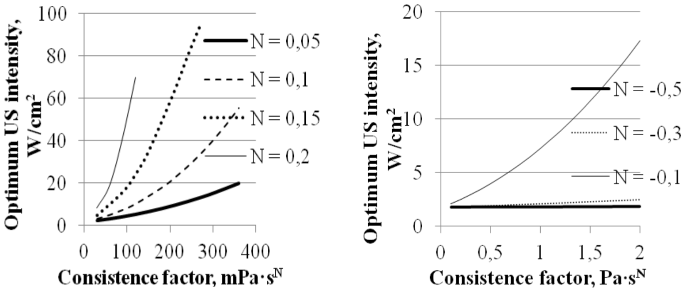


a) b)

Fig. 1. Dependences of attenuation coefficient on intensity of action for low-viscous (a) and high-viscous (b) liquids

Maximum value of attenuation coefficient corresponds to maximum part of energy spent to collapse of cavitation bubbles, that is why, intensity, at which it achieves, is optimum. As it follows from the dependences shown in Fig.1 obtained results agree with the results of the experiments carried out before [3, 5]. Obtained values of attenuation coefficient varying in the range of 0.1...0.8 dB/cm are used further for finding of the form and sizes of cavitation area in different technological volumes.

As the most of polymer and composite materials processed in practice are nonlinear-viscous liquids, and influence of the modes of ultrasonic action on the development degree of the cavitation process in such liquids was not considered, Fig.2 shows obtained dependences of optimum intensities of action on consistency indices for this class of liquids at different nonlinearity indices. The consistency index characterizes the value of strength of hydrogen bonds of processed materials under the action of ultrasonic cavitation, and the nonlinearity index depends on ability of hydrogen bonds to form new bonds.

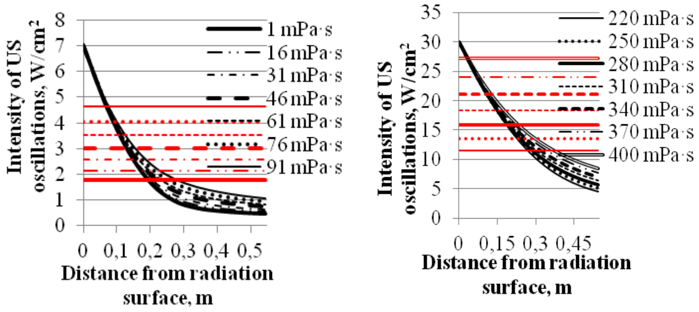


a) b)

Fig. 2. Dependences of optimum intensity of ultrasonic action on the consistency factors for dilatancy (a) and pseudoplastic (b) liquids

As it follows from obtained dependences, for dilatancy liquids (see Fig.2a) very high intensity of action (upto 100 W/cm²) can be required, however for pseudoplastic liquids (see Fig.2b) (at nonlinearity indices of -0.3 and less) intensity of action of 2...3 W/cm² is sufficient in a wide range of consistency indices.

As to increase the efficiency of cavitation processing the mode of developed cavitation should be generated in the area of maximum size, we carried out analysis of formation of cavitation area for various conditions of propagation of ultrasonic vibrations, the dependences of intensity changes of ultrasonic vibrations (see Fig.3) on the distance from radiating surface taking into account attenuation of ultrasound due to the cavitation at the application of mushroom-shaped working tools were obtained .



a) b)

Fig. 3. Dependences of intensity of ultrasonic vibrations on the distance of radiating surface in unlimited volumes (red line marks the threshold intensity, at which the mode of developed cavitation is achieved)

As it follows from presented dependences, for high-viscous liquids the size of developed cavitation area does not exceed 3 cm.

Such small value of sizes of cavitation area generated in unlimited volumes (without reflections) causes the necessity of search of ways of this area extension due to the generation of standing waves in specialized technological chambers.

We take a construction of technological chamber of flowing reactor, which is a metal cylindrical cave of constant diameter, as a base for the search of optimum construction diagrams. In the technological chamber as it is shown in Fig.4, there is a multizone working tool of stepped variable diameter (70x50 mm) with enlarged radiation surface.

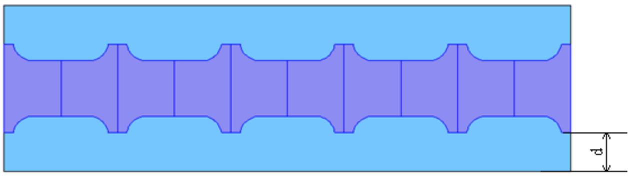


Fig. 4. Simple cylindrical technological volume with installed radiator (d is the distance between the edge of ledge of the disk radiator and the wall of the technological volume)

The efficiency of operation of the technological chamber is determined by the volume of developed cavitation area, i.e. the volume, in which amplitude of acoustic pressure P lies in the range of $P_1 < P < P_2$, where P_1 is the threshold amplitude of acoustic presssure, at which the mode of developed cavitation is reached, P_2 is the maximum amplitude of acoustic pressure, at which bubbles begin to degenerate into long-lived, reducing to zero the efficiency of cavitation action on technological medium. P_1 and P_2 are defined on the base of the model described above. For model liquid the value of P_1 is $4.4 \cdot 10^5$ Pascal, and P_2 is $12 \cdot 10^5$ Pascal, that correspond to intensity of action of 3.2 W/cm^2 (for P_1) and 24 W/cm^2 (for P_2).

The definition of acoustic pressure in the chamber and calculation of the sizes of cavitation area was carried out in software environment COMSOL MultiPhysics.

Fig.5 shows the dependences of useful volume (the volume of technological medium, at which the mode of developed cavitation is realized) on the diameter of cylindrical chamber, and Fig.6 shows the fraction (in percents) of useful processed volume on the diameter of the cylindrical technological volume.

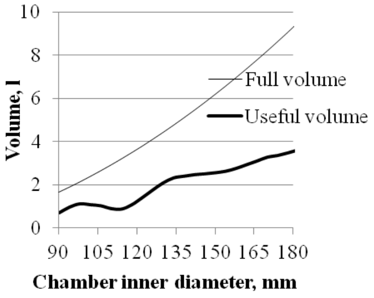


Fig. 5. Dependences of total and useful volume of processed liquid in the cylindrical technological chamber on its internal diameter

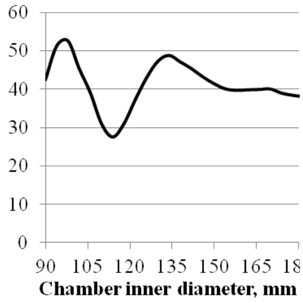


Fig. 6. Dependence of the fraction of useful processed volume on internal diameter of the technological chamber

As it follows from presented dependences, at the cylinder diameter of 98 mm maximum fraction of the volume of processed liquid is achieved, in which the mode of developed cavitation (more than 50%) is realized. However at this diameter absolute value of useful volume does not exceed 1.2 l, that is why, in the case of simple cylinder optimum diameter is 134 mm (useful volume exceeds 2 l).

The distributions of acoustic pressure and form of the areas, in which the mode of developed cavitation is realized, for cylindrical volume with the internal diameter of 134 mm are shown in Fig.7 and in Fig.8, respectively.

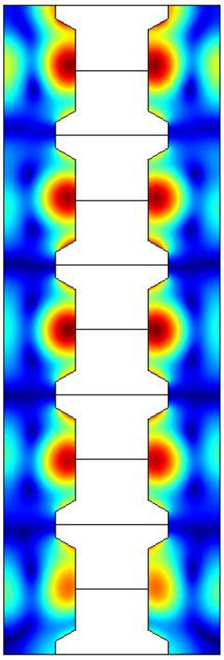


Fig. 7. Distribution of acoustic pressure in cylindrical technological chamber

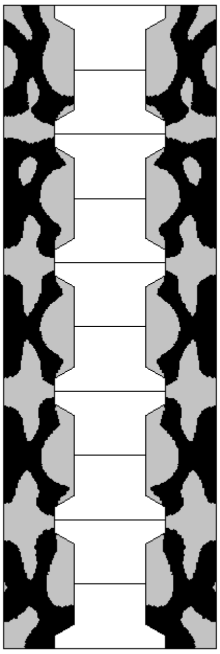


Fig. 8. Distribution of the areas of developed cavitation (marked by black colour) in cylindrical volume

To increase the efficiency of cavitation action in the technological volumes it is proposed to install reflecting ledges [4], as it is shown in Fig.9.

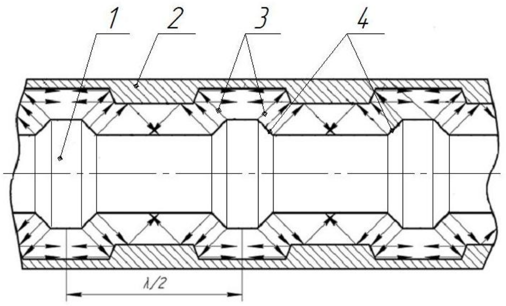


Fig. 9. Scheme of propagation of ultrasonic vibrations in the technological chamber with reflecting ledges

The location and the forms of the areas of developed cavitation in the chamber of proposed construction is shown in Fig.10.

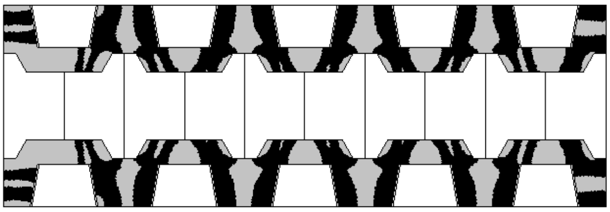


Fig. 10. Distribution of the areas of developed cavitation in the technological chamber with reflecting ledges

As it follows from Fig.10, reflecting effect leads to more uniform distribution of acoustic pressure. Fig.11 shows the dependence of the fraction (in percent) of useful volume on the size of reflecting ledge, and Fig.12 shows the dependences of total and useful volume on the size of reflecting ledge.

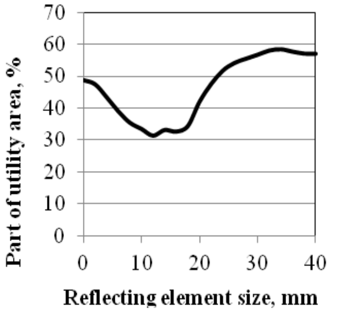


Fig. 11. Dependence of the part of useful volume on the size of reflecting element

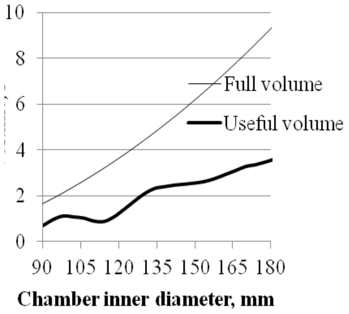


Fig. 12. Dependence total and useful volume of processed liquid in the cylindrical technological chamber with reflecting ledges on its internal diameter

As it follows from presented dependence the fraction of useful volume can achieve 60% at the diameter of the cylindrical chamber of 134 mm (without reflecting ledges it does not exceed 50%). However, as it is evident from Fig.12, absolute value of useful volume was less at the absence of these ledges.

The analysis of possibilities to install different in form additional reflectors in the places of joint of separate waveguides of working tool in the technological volumes allows to obtain following results of distribution of areas of developed cavitation (see Fig.13).

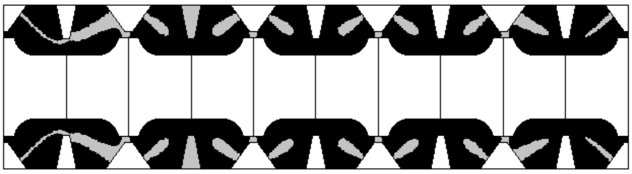
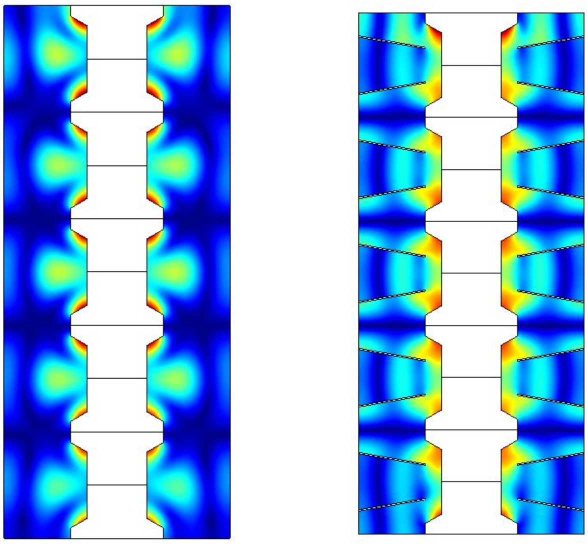


Fig. 13. Distribution of areas of developed cavitation in the technological chamber with additional reflectors near the places of joints of the waveguides of working tool

In spite of the fact, that such construction provides more uniform distribution of acoustic pressure in comparison with previous variant, the reflectors in the places of joints of waveguides shut down the section of the flow of liquid processed in flowing mode. This fact is caused by enlarged diameter of the parts of working tool in the places of joints of the waveguides.

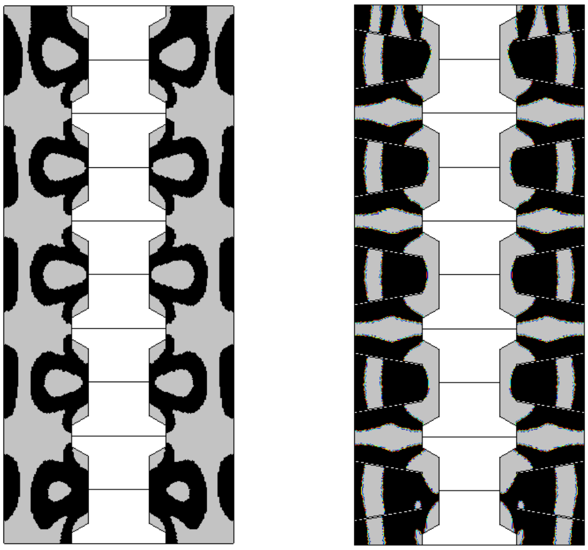
To prevent decrease of total volume of processed liquid we consider the possibility of the application of thin plates with round holes with the diameter of less than wave length as a reflector, the presence of which does not reduce the volume of processed liquid. The optimization of plates location is made for the chamber with the diameter of 170mm, as at such diameter total volume exceeds 7 l at relatively high portion useful volume (40%) without plates.

Comparative distributions of acoustic pressure and the areas of developed cavitation with (b) and without (a) reflecting plates are shown in Fig.14, Fig.15.



a) without reflecting plates b) with reflecting plates

Fig. 14. Distribution of acoustic pressure



a) without reflecting plates b) with reflecting plates

Fig. 15. Distribution of developed cavitation area

As it follows from presented figures, the use of reflecting plates leads to essential increase of summarized volume of the areas of developed cavitation and consequently to more uniform processing of liquid.

Fig.16 shows the dependence of useful volume (total volume of the area of cavitation action) on oncoming slope angle of reflecting plates to cross-sectional plane of the chamber.

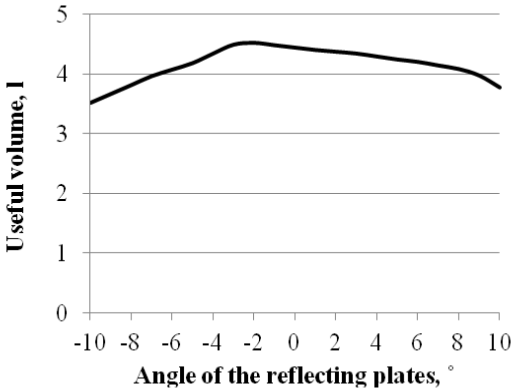


Fig. 16. Dependence of useful volume on slope angle of reflecting plates

As it follows from presented dependence, there is a slope angle, at which maximum size of useful volume is achieved. At optimum angle (-2 degrees) the useful volume is about 4.5 l, while at absence of reflecting plates it does not exceed 3 l, that proves the possibility to increase efficiency of processing in 50% (in 1.5 times) in the reactors of flowing type.

IV. CONCLUSION

Carried out researches allow to determine laws of formation of cavitation areas in nonlinear-viscous liquids under the action of ultrasonic vibrations radiated from the surface of multi half-wave working tool. The analysis of proposed model lets define, that the attenuation coefficient can be in the range of 0.1 to 0.9 dB/cm, it depends on intensity of ultrasonic vibrations and it defines the efficiency of cavitation action.

The model allows to study influence of the conditions of propagation and reflection of ultrasonic vibrations (size and form of the technological chamber) on summarized volume occupied by the area of the most effective cavitation action, which determines the efficiency of processing.

Carried out studies let ascertain following facts:

– the use of cylindrical technological chambers of cross-section allows to provide uniformity of cavitation action, however it does not allow to increase real efficiency of processing;

– the application of additional reflecting plates with the holes leads to the increase of processing efficiency in no less than 50%.

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