Theoretical explanation of the ultrasonic action pulsed mode on liquid to reduce cavitation

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Abstract. The article is devoted to theoretical studies of the possibility of reducing cavitation in a medium by using a pulsed exposure mode. A model of the formation and propagation of pulsed ultrasonic vibrations in a liquid is proposed. Pulse shapes are obtained taking into account the distortions arising in the technological volume. On the basis of the identified shapes, the shapes and positions of cavitation zones were calculated, which showed a decrease in the volume of zones in which cavitation bubbles arise under impulse action compared to continuous.

1. Introduction
In most chemical-technological processes, ultrasonic (US) vibrations are used to increase the efficiency of their implementation [1–5]. One of the main influencing factors of ultrasonic vibrations is cavitation, in which a low energy density of a propagating wave is transformed into a high energy density formed after the collapse of a cavitation bubble, a cumulative jet or shock full. The action of cavitation makes it possible to accelerate numerous technological processes associated with changes in the structure and properties of liquid materials. However, cavitation also has a negative effect on the course of processes [5]. This is due to the appearance of a zone of vapor-gas bubbles near the radiator, which is characterized by anomalously high absorption of vibration energy and restricts the further propagation of vibrations.

In addition, cavitation is absolutely unacceptable for many processes, where ultrasonic vibrations create a directed stimulating and unifying effect [5–8]. Such processes include the destruction of emulsions, coagulation of solid particles (where cavitation can destroy the formed agglomerates), processes of uniform distribution of nanoparticles in viscous media, bacterial water purification, fermentation (where cavitation can destroy yeast bacteria), processes of liquefaction of natural substances - for example, honey (where cavitation can have a negative effect on beneficial properties).

It has been established in practice that under continuous sinusoidal action [9], collapsing cavitation bubbles may form at intensities ranging from 0.3W/cm² (in water).

Thus, it is impossible to introduce and distribute large energies over long distances and effectively implement processes that do not allow cavitation.

The solution to the problem can be the use of short ultrasonic pulses for influencing the processes [10, 11], which can be formed by emitting sinusoidal oscillations modulated in amplitude by periodic rectangular pulses. In this case, the generated ultrasonic pulses will represent one after another wave packets of finite duration, greater than the period of ultrasonic vibrations, but less than the repetition

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period of the packets (figure 1). Experiments have shown that ultrasonic pulses [9] will lead to a decrease in cavitation at the same total input acoustic energy.

Figure 1. Vibration form of ultrasonic pulses.

However, to date, pulsed ultrasonic exposure is not used in practice due to the lack of sufficient scientific substantiation of the necessary modes and conditions for the implementation of the process. To date, the most fully (both experimentally and theoretically) investigated ultrasonic pulsed action for the case of unlimited volume and plane wave, when the phenomena of reflection, interference and diffraction divergence of waves do not affect the shape of the pulses and, consequently, the efficiency of the process [5, 9-11].

In this regard, the paper proposes a model for the formation and propagation of ultrasonic pulses and the cavitation zone, which made it possible to substantiate the effectiveness of ultrasonic pulsed exposure to reduce cavitation in technological volumes close to real ones, taking into account the reflection, interference and diffraction divergence of acoustic waves.

2. Mathematical formulation of the problem

The formation and propagation of ultrasonic pulses is simulated in a cylindrical technological volume with a submerged piston emitter (figure 2). The technological volume has a diameter $D$, an ultrasonic emitter has a diameter $D_{\text{rad}}$. The simulated process volume has absolutely elastic walls and is filled with liquid. Opposite to the ultrasonic transducer, there is a porous medium that has finite elasticity and partially absorbs vibrations. Such a configuration takes place, in particular, in various processes of liquid purification (when ultrasound intensifies the separation of homogeneous binary or heterogeneous mixtures, initially realized with the help of an adsorbent or a membrane system).

The formation and propagation of oscillations in such a volume is described using a nonstationary wave equation (1):

$$\frac{\partial^2 p}{\partial r^2}(r, z, t) + 1 \frac{\partial p}{r \partial r}(r, z, t) + \frac{\partial^2 p}{\partial z^2}(r, z, t) - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}(r, z, t) = 0;$$  \hspace{1cm} (1)

with the boundary conditions for the generation of oscillations on the surface of the emitter, absolutely elastic reflection of vibrations from the side wall of the process volume and reflection, and absorption of vibrations at the interface "liquid-porous medium" located opposite the emitter.

Figure 2. Model technological volume for analyzing the propagation of ultrasonic pulsed vibrations and the formation of the cavitation region.
Taking into account the boundary conditions, the wave equation (1) is solved by expanding in a series in terms of the 0-th order Bessel functions in conjunction with the method of separation of variables (2):

\[
p(r, z, t) = \sum_{n=1}^{\infty} \sum_{m=0}^{\infty} x_{nm} J_0(K_m r) \text{Re} \left( 2P_n L_{n,m}(z) e^{-i\omega_m t} \right); \tag{2}
\]

\[
L_{n,m}(z) = e^{i\left(\frac{\omega_m^2}{c^2}z - K_m^2(z - H)\right)} + B_{n,m} e^{-i\left(\frac{\omega_m^2}{c^2}z - K_m^2(z - c)\right)};
\]

\[
Z(\omega) = \frac{n\omega}{\sqrt{n^2 \omega^2 - c^2 K_m^2}};
\]

where:
- \(x_{nm}\) coefficients determined by the geometry of the gap between the radiator and the side wall, the radiator itself and the distribution of vibration amplitudes on the surface of the radiator;
- \(K_m\) coefficients defining the “zeros” of the derivative of the 0-th order Bessel function
- \(P_n\) Fourier expansion coefficients for sound pressure near an oscillating infinite flat surface in the absence of a reflector (the amplitude of oscillations of this surface is exactly the same as at the center of the model piston radiator)

\[
p_{\text{inf}}(t) = \sum_{n=1}^{\infty} \left( P_n e^{-i\omega_n t} + P_n^* e^{i\omega_n t} \right) = \left\{ \begin{array}{ll} \rho c A \cos(\omega t), & \exists n \in Z, 0 \leq t - nT \leq \tau \\ 0, & \neg \exists n \in Z, 0 \leq t - nT \leq \tau \end{array} \right., \text{ Pa};
\]

\[
\rho - \text{density of liquid kg/m}^3;
\]
- \(c\) – speed of sound in liquid, m/s;
- \(\omega\) – circular vibration frequency of an ultrasonic transducer, s\(^{-1}\);
- \(A\) – vibration amplitude of the center of the ultrasonic emitter surface, m;
- \(T\) – repetition period of ultrasonic pulses, s;
- \(t\) – time, s;
- \(\tau\) – pulse duration, s;
- \(Z(\omega)\) – the relative value of the mechanical impedance of the porous medium (relative to the wave resistance of the liquid).

Based on the found distribution of sound pressure, the distribution of cavitation zones (zones with collapsing cavitation bubbles) was calculated. The distribution of cavitation zones (presence or absence of collapse of bubbles at each observed point) was calculated using the equation of rectified diffusion [5].

A method and an algorithm for solving this equation is proposed, taking into account changes in the pressure amplitude over time due to the interference of pulses.

The resulting distributions and dependencies are presented in the next section.

3. Results of calculations

The distributions of the amplitude of the sound pressure were obtained (figure 3)

\[
P_{\text{MAX}}(r, z) = \max_{t \in [0, T]} |p(r, z, t)|;
\]

and pulse shapes (figure 4) at different points of the process volume (diameter of the process volume - 0.08 m; height - 0.12 m) at the oscillation frequency of a separate wave packet created by the emitter (emitter diameter - 0.072 m), 22 kHz, liquid - water under normal conditions.
Figure 3. Model technological volume for analyzing the propagation of ultrasonic pulsed vibrations and the formation of the cavitation region.

Figure 4. Pulse shapes (relative sound pressure versus time) at different points of the process volume.
From the presented figures it follows that when the pulses are distorted due to reflections and interference, the ratio of the maximum value of the pulse envelope to the minimum can be up to 10 times or less. This is essential for the rate of slow bubble growth due to rectified diffusion. Those, the bubble will grow during the entire period of pulse repetition and, consequently, reaching the size at which the bubble is able to rapidly expand and collapse, possibly with a lower amplitude of sound pressure than with undistorted pulses. For an objective study of the possibility of cavitation, taking into account reflections and interference, the distributions of cavitation zones were calculated, shown in figure 5.

**Figure 5.** Distribution of cavitation zones in the process volume (blue zone - bubbles do not collapse, orange zone - bubbles collapse) under continuous and impulse action and at various reduced pressure amplitudes throughout the volume.

\[ P_{\text{EFF}} = \rho c \omega A; \rho c \omega \text{ – wave resistance of liquid, kg/m}^2\text{s; } \omega \text{ – circular vibration frequency of an ultrasonic transducer, s}^{-1}; A \text{ – vibration amplitude of the ultrasonic emitter, m}. \]

The presented figures indicate the possibility of reducing cavitation due to the use of a pulsed exposure mode compared to continuous exposure in a wide range of sound pressure amplitudes in a limited technological volume.

For example, at a reduced sound pressure amplitude of 200 kPa, continuous exposure leads to the formation of a cavitation zone near the radiator, while at the same sound pressure amplitude and impulse action, a cavitation zone is not formed. At higher amplitudes of sound pressure (from 250 kPa and above), a decrease in the volume of the cavitation zone by more than 3 times is observed.

This confirms the effectiveness of ultrasonic impulse exposure in technological volumes used in practice.

4. Conclusion

Thus, as a result of the research carried out, a model of the formation and propagation of pulsed ultrasonic vibrations in a liquid has been proposed. Pulse shapes are obtained taking into account the distortions arising in the technological volume due to interference and reflections of oscillations. On the basis of the identified pulse shapes, the shapes and positions of cavitation zones were calculated, which showed at least a 3-fold decrease in the volume of zones in which cavitation bubbles arise under impulse action compared to continuous.

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