

Registration of the cavitation regime in liquids under the action of ultrasonic vibrations

Pavel Vikulin and Vera Vikulina

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: vikulinp@yandex.ru

Abstract. Ultrasonic vibrations are widely used in various industries and production: in metallurgy, in the chemical and food industries, in mechanical engineering, and in medicine. This is due to the physicochemical changes in the substance when superimposed sound fields. Cavitation in the ultrasonic field causes dispersion and emulsification of certain substances, promotes coagulation and degassing, affects the processes of crystallization and dissolution, it is known that ultrasonic vibrations cause a variety of chemical transformations of the substance, including oxidation, reduction, polymerization and depolymerization reactions. The researchers find the explanation of these phenomena in the diverse effect of cavitation on matter: shock waves, micro streams, acoustic wind. The experiments were carried out in a liquid medium (un-distilled water). The volume of the experimental test was 10 dm³. To obtain ultrasonic vibrations, the method of magnetostriction was used, the principle of which is to convert electric oscillations into mechanical ones. To assess the cavitation regime, the level of cavitation was recorded in two stages: the degree of erosion of the artificial obstacle, the measurement of the intensity of the cavitation noise in the volume

1. Introduction

The physical nature of ultrasound

Ultrasound - elastic vibrations. Ultrasonic waves of high intensity are described only by the laws of nonlinear acoustics. The propagation of ultrasonic waves in liquids is accompanied by acoustic flow, condensation, and medium discharge. Acoustic cavitation is among the important nonlinear phenomena in an ultrasonic field.

Investigation of the mechanism of the action of acoustic fields on the matter is complicated by the fact that there are simultaneously different processes in the ultrasonic field that can have mutual influence. Therefore, it is difficult to describe the experimental results. At the present time, theoretical grounds for the use of physical methods, in particular, ultrasonic vibrations, in water technologies are being developed. The use of an ultrasonic field to intensify oxidation-reduction processes in an aqueous medium, the precipitation of coarsely dispersed impurities expands the area of possible use of this physical method [1, 2, 3, 4].

Sound, as a physical phenomenon, is characterized by the sound pressure, the density of sound energy, the flow of sound energy, the level of intensity (power) of sound. Liquids in the static state do not have a shear viscosity and are incapable of withstanding and transmitting any tangential stresses. Therefore, only longitudinal waves propagate in liquids and gases, in which the direction of the tangential motions of the particles coincides with the direction of propagation of the waves. The



propagation velocity depends on the density of the medium ρ and the adiabatic compressibility coefficient β_c and is calculated from the formula:

$$c = \sqrt{\frac{1}{\rho \cdot \beta_c}} \quad (1)$$

The physical nature of propagation of elastic waves is described by equation

$$y = A \cdot \sin \omega \cdot t \quad (2)$$

where A – bias amplitude;

ω – cyclic frequency;

t – a period of time.

Acoustic vibrations in the medium create additional pressure [5, 6, 7]. The sound wave, passing through the liquid, creates zones of compression and depletion, changing places in each half-period of the passage of the wave. This gives rise to a sign-variable pressure, P , which can be determined from formula:

$$P = \sqrt{\rho \cdot c \cdot I} \cdot 4.6 \cdot 10^{-3} \quad (3)$$

Sound pressure is a variable that varies periodically. At a given point in the medium, during a period, the pressure P changes from a maximum to zero and then rises again to a maximum value, and corresponds to a description of harmonic oscillations:

$$P = P_{\max} \cdot \sin \omega \cdot t, \quad (4)$$

where $P_{\max}$ is the maximum sound pressure (pressure amplitude), defined by formula

$$P_{\max} = \omega \cdot c \cdot \rho \cdot A, \quad (5)$$

where c – speed of sound.

When ultrasound propagates in the medium, part of its energy is absorbed, and the medium heats up. Absorption of acoustic energy is due to the frequency of sound, viscosity, thermal conductivity and wave resistance of the medium, i.e. the product of the density of the medium ρ and the speed of sound. The relationship between the sound pressure developed in the medium and the wave impedance expresses the vibrational velocity. [8, 9]

The value of the wave impedance of the medium is determined by the ratio of the sound pressure in the traveling plane wave to the vibrational velocity of the particles of the medium V

$$\frac{P}{V} = r \quad (6)$$

Vibrational velocity and sound pressure do not depend on frequency, the amplitude of the oscillations is inversely proportional, and the acceleration is directly proportional to the frequency. Usually the amplitudes of the vibrational velocities are many orders of magnitude lower than the sound velocity in the unperturbed liquid (10^3 m/s).

For moderate acoustic fields, the sound pressure usually does not exceed 1 MPa, but the pressure gradient, especially at high frequencies, can reach large values. The amplitude of the acceleration of liquid particles in the field of ultrasonic waves is great, they can exceed the acceleration of free fall by several orders of magnitude. In technology such accelerations are achieved only in special ultracentrifuges. Also taking into account the fact that such values of acceleration change sign twice during the period, one can consider ultrasonic waves a very powerful and peculiar physical factor affecting the substance even in the absence of nonlinear effects.

Physicochemical and chemical effects in a liquid medium under the action of ultrasonic cavitation.

The main physicochemical and chemical effects that arise in a liquid under the action of acoustic fields are due mainly to nonlinear effects, of which the most important is cavitation [10, 11, 12, 13]. One of the characteristic features of ultrasonic cavitation is that it is a peculiar and effective mechanism of local concentration of relatively low average energy of the acoustic field in very small volumes, which leads to the creation of exceptionally high energy densities.

The detailed mechanism of this effect is not yet completely clear. In connection with the fact that the phenomenon of cavitation represents a great theoretical and practical interest in the basic physicochemical problems of cavitation, considerable attention will be paid subsequently.

The wave resistance of the medium is a very important characteristic that determines the conditions for radiation, absorption of acoustic vibrations, their reflection, refraction, etc.

Particles of the elastic medium in which ultrasonic waves propagate vibrate and therefore possess kinetic and potential energy.

The amount of energy transferred by sound vibrations per second through an area of 1 sm^2 , which is perpendicular to the direction of their propagation, characterizes the intensity of sound and is determined by the formula:

$$I = E_1 \cdot c, \quad (7)$$

where E_1 – energy density.

The density of sound energy at each point varies with time. The average value of the energy density at a given point is determined by the formula

$$E_1 = \frac{1}{2} \cdot A^2 \cdot \omega^2 \cdot \rho. \quad (8)$$

Transforming equation (7) and equation (8) we obtain expression (9)

$$I = \frac{1}{2} \cdot A^2 \cdot \omega^2 \cdot \rho \cdot c. \quad (9)$$

In the propagation of sound waves in a liquid medium, the intensity of sound I decreases with increasing distance from the source of radiation from equation:

$$I = I_0 \cdot e^{-2\alpha X}, \quad (10)$$

where I_0 – sound intensity at $X = 0$,

α – absorption coefficient.

The absorption coefficient depends on the physical properties of the substance, it is a parameter characteristic of the substance, and also depends on external conditions (temperature, pressure) and on the frequency of oscillations.

Although the physical nature of ultrasound and the basic laws describing its propagation are the same as for sound waves of any frequency range, it has a number of specific features. These features are due to its relatively high frequencies and correspondingly small wavelengths [14, 15, 16].

Thus, for high ultrasonic frequencies, the wavelengths are:

$3.4 \cdot 10^{-3} - 3.4 \cdot 10^{-5} \text{ cm}$	in the air,
$1.5 \cdot 10^{-2} - 1.5 \cdot 10^{-4} \text{ cm}$	in the water,
$5 \cdot 10^{-2} - 5 \cdot 10^{-4} \text{ cm}$	and in metal.

Ultrasonic waves decay much faster than the waves of low-frequency sound range since the coefficient of "classical" sound absorption (per unit distance) is proportional to the square of the frequency.

In the low-frequency region, the relaxation absorption coefficient also increases in proportion to the square of the frequency, but as the frequency increases, this growth decreases, and the absorption coefficient tends to a constant value.

The relationship between the nature of the propagation of ultrasound and, in particular, its high-frequency area - hypersound with the structure of matter and elementary excitations in it - is one of the most important features of ultrasonic waves. It allows us to judge the structure of matter on the basis of measurements of velocity and absorption in it, depending on the frequency, as well as on certain external factors - temperature, pressure, etc.

A feature of ultrasound in the high-frequency and hypersonic ranges is the possibility of using the methods of quantum mechanics, since the wavelengths and frequencies of sound in these ranges become of the same order with parameters and frequencies characterizing the structure of matter.

An elastic wave of a certain frequency is then associated with a photon quasiparticle, or a quantum of sound energy. Representations from quantum mechanics are convenient when considering various

interactions in solids. For example, the scattering and absorption of sound by vibrations of the crystalline lattice can be regarded as the interaction of coherent and thermal phonons.

In a high-intensity ultrasonic field, considerable acoustic currents develop, the velocity of which, as a rule, is small in comparison with the vibrational velocity of the particles [17, 18, 19].

Currents can be due to sound absorption, can occur in standing waves or in the boundary layer near obstacles of a diverse type (Figure 1).



Figure 1. The photo. Acoustic flow, which occurs when the propagation of ultrasonic oscillations with a frequency of 5 MHz in benzene.

Radiation pressure also increases with increasing frequency, since its magnitude is proportional to the intensity of sound; in the ultrasonic frequency range. It is used in the practice of acoustic measurements to determine the intensity of sound.

In order for the parameters determining the various effects of the sound field-sound intensity, sound pressure, vibrational velocity, radiation pressure - to reach a noticeable value, as the frequency increases, an ever smaller value of the amplitude of the vibrational displacement is required.

The most important nonlinear effect in the ultrasonic field is cavitation - the appearance in the liquid of a mass of pulsating bubbles filled with steam, gas or a mixture thereof [20]. The complex motion of bubbles, their slamming, merging with each other, etc., generate compression pulses (micro-impact waves) and micro-streams in the liquid, cause local heating of the medium, ionization. These effects affect the substance: the solid particles in the liquid are destroyed, (cavitation erosion), fluid mixing occurs, various physical and chemical processes are initiated or accelerated. By changing the conditions of cavitation, various cavitation effects can be intensified or weakened, for example, with the increase in the ultrasound frequency, the role of microflows increases and cavitation erosion decreases, with the increase in hydrostatic pressure in the liquid, the role of microscopic impacts increases.

An increase in the frequency of oscillations usually leads to an increase in the threshold value of the intensity corresponding to the onset of cavitation, which depends on the nature of the liquid, its gas content, temperature, etc. For water in the low-frequency ultrasonic range at atmospheric pressure, the intensity is usually 0.3-1 W / cm² (figure 2).



Figure 2. Photo. A fluid fountain formed by the radiation of an ultrasonic beam from the depth of the liquid to its surface (the radiation frequency is 1.5 MHz, the intensity is 15 W / cm²).

The diverse applications of ultrasonic vibrations, in which different features are used, can be conditionally divided into three directions. The first is due to the acquisition of information by means of ultrasonic waves, the second - with the active effect on the substance and the third - with the processing and transmission of signals [21].

The aim of the work.

The aim of this work is to confirm the existence of a cavitation regime and to identify the nature of the distribution of the cavitation intensity in the volume of the liquid.

The task of the work.

The task of the work is to determine the developed cavitation in terms of the degree of erosion (destruction) of the artificial obstacle, and also to obtain a graphic representation of the intensity of ultrasonic cavitation in the volume of the reactor of the experimental apparatus for treating liquids.

Apparatus and methods for conducting experimental studies.

Ultrasonic equipment UZG - 2 - 4 was used in a set with PMS - 6 - 22

The main technical characteristics of ultrasonic generator UZG – 2 – 4

Generator output power, kW	4.5 ± 0.5
Output voltage, V	360 ± 80
Output frequency (adjustable), kHz	16.8 – 19.2 20.5 – 23.5
Coefficient of efficiency, %, not less than	75
Supply voltage (three-phase, with neutral wire), V	$360 \pm 5\%$
Frequency of supply voltage, Hz	50
Weight, kg, no more than	250
Overall dimensions, mm	720 x 580 x 1350

Main technical characteristics of the magnetostrictive converter PMS - 6 – 22

Consumed power, no more than	2.5 kW
Supply voltage	360 ± 80 V
Operating frequency	22 ± 1.65 kHz
Weight, not more than	11kg
dimensions	300 x 300 x 191 mm

To carry out experimental studies on the effect of ultrasonic vibrations on water purification processes in the NRU of the MSCU at the Chair of Water Management and Water Supply, the ultrasonic reactor was made of XI8HICT stainless steel with the introduction of acoustic oscillations from below upwards through the thickness of the liquid in the volume of the reactor at atmospheric pressure to the water surface.

The ultrasonic reactor is rectangular in shape, equipped with magnetostrictive converter PMS – 6 - 22, reactor dimensions in the plan 400mm x 400mm (membrane size 300mm x 300mm), the liquid depth in the reactor reaches 300mm. The transducer of acoustic oscillations is placed in the lower part of the reactor, under a layer of liquid. The scheme of the experimental installation of liquid treatment in an ultrasonic field is shown in Fig. 3.

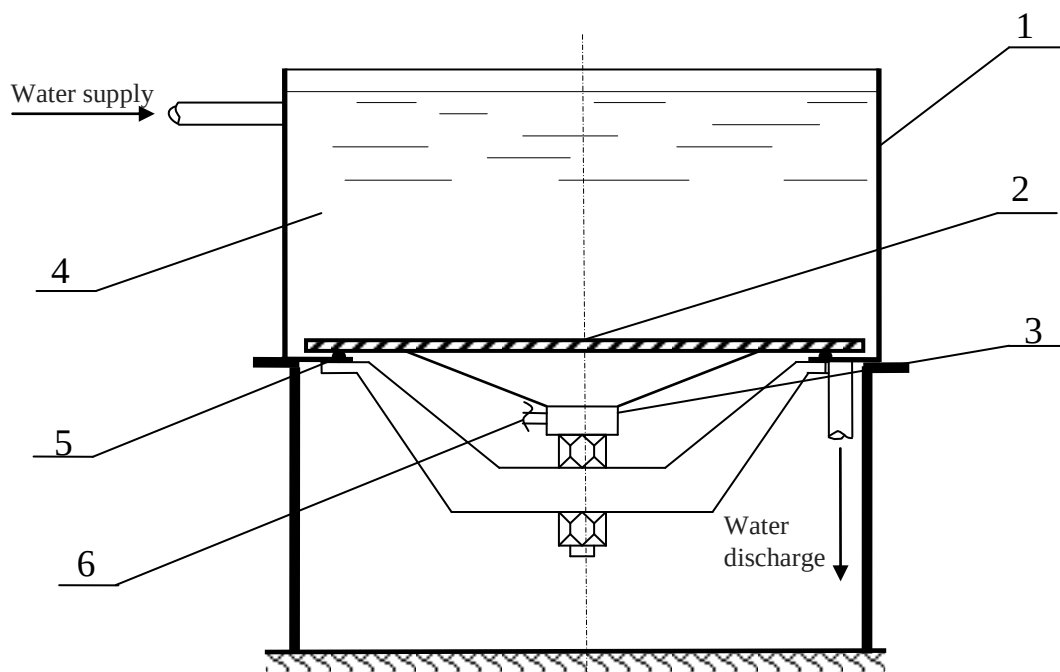


Figure 3. The scheme of the experimental construction. 1. Reactor made of stainless steel of grade XI8HICT; 2. Membrane emitting ultrasonic waves from the bottom to the top; 3. Magnetostrictive transducer PMS – 6 - 22; 4. Treated liquid; 5. Sealed (rubber) gaskets; 6. Cooling liquid.

The basis of the processes of ultrasonic action on the liquid medium is the cavitation regime. Therefore, reliable registration of the flow of cavitation phenomena is desirable. It is expedient to carry out experimental studies in two stages.

First stage. Evaluate the collapse of cavitation cavities, in a liquid, under the influence of ultrasonic vibrations, according to the degree of erosion of the artificial barrier (indicator). For this purpose, a foil tape 400 mm x 300 mm in size is used as an indicator, it is immersed in a liquid, in which a cavitation effect is observed.

The bubbles that are formed in the ultrasonic field collapse and create microexplosions, shock waves, and microflows. Cavitation cavities, which are formed near the foil web, inevitably lead to erosion of the web itself. In the case of a powerful effect of ultrasonic vibrations, it is possible to partially or completely destroy the foil web.

The intensity of the cavitation regime depends on the chemical composition of the liquid, on the intensity of the ultrasonic field, and on the emitting ability of the ultrasonic oscillation source. In our case, the emitter and the liquid remain constant, therefore, the chemical composition of the medium, the exposure to ultrasound and the sample temperature may change.

As samples for the example of visual registration of the cavitation regime, we choose two liquid media, water and industrial wastewater of the primary processing of wool.

A foil web of 400 mm x 300 mm in size, 15 microns thick in a special frame, is placed in the reactor perpendicular to the radiating surface to the height of the sample, as if dissecting the depth in the reactor in half, from the radiator to the upper edge of the free surface of the liquid.

The temperature of the initial water sample was 13 °C, and the duration of the ultrasonic exposure to the blade was 10 min. For sewage, the exposure varied from 10 seconds to 10 minutes, and the water temperature was 38 °C.

Second stage. They begin to pulsate in phase with the active acoustic field in the process of propagation of ultrasonic vibrations in the water of the microcavity. At the same time, in the process of cavitation, ultrasound is emitted as the fundamental frequency, and with the addition of harmonic components of sound radiation, collapsing cavitation cavities. The registration of these sound effects

can be performed with the aid of a device that measures acoustic radiation, filtering out and eliminating the noise of the fundamental frequency. Such a device was created and tested at the Chair of Water Supply and Sanitation of the Moscow SRI MG.

As a result of the research it was determined that zones with different cavitation intensity and density exist in the reactor under the action of an ultrasonic field. To identify areas of cavitation zones, this device was used, which makes it possible to measure the intensity of sound pressure when an ultrasonic field is applied at any point in the reactor. This device is capable of recording the sound pressure resulting from the collapse of the cavitation cavity.

2. Results

At the first stage of the experimental studies of cavitation regime registration by erosion of the foil web (the foil web size is 300 x 400 mm.) are shown in Fig. 4 (a, b, c, d, e). The lower horizontal part of the foil was in close proximity to the radiator. Accordingly, the upper horizontal part of the foil web was located on the free surface of the liquid.

Below are photographs of real images with traces of cavitation erosion on the foil web. The resulting images, shown in Figure 4, confirm the presence of a cavitation regime in a liquid.

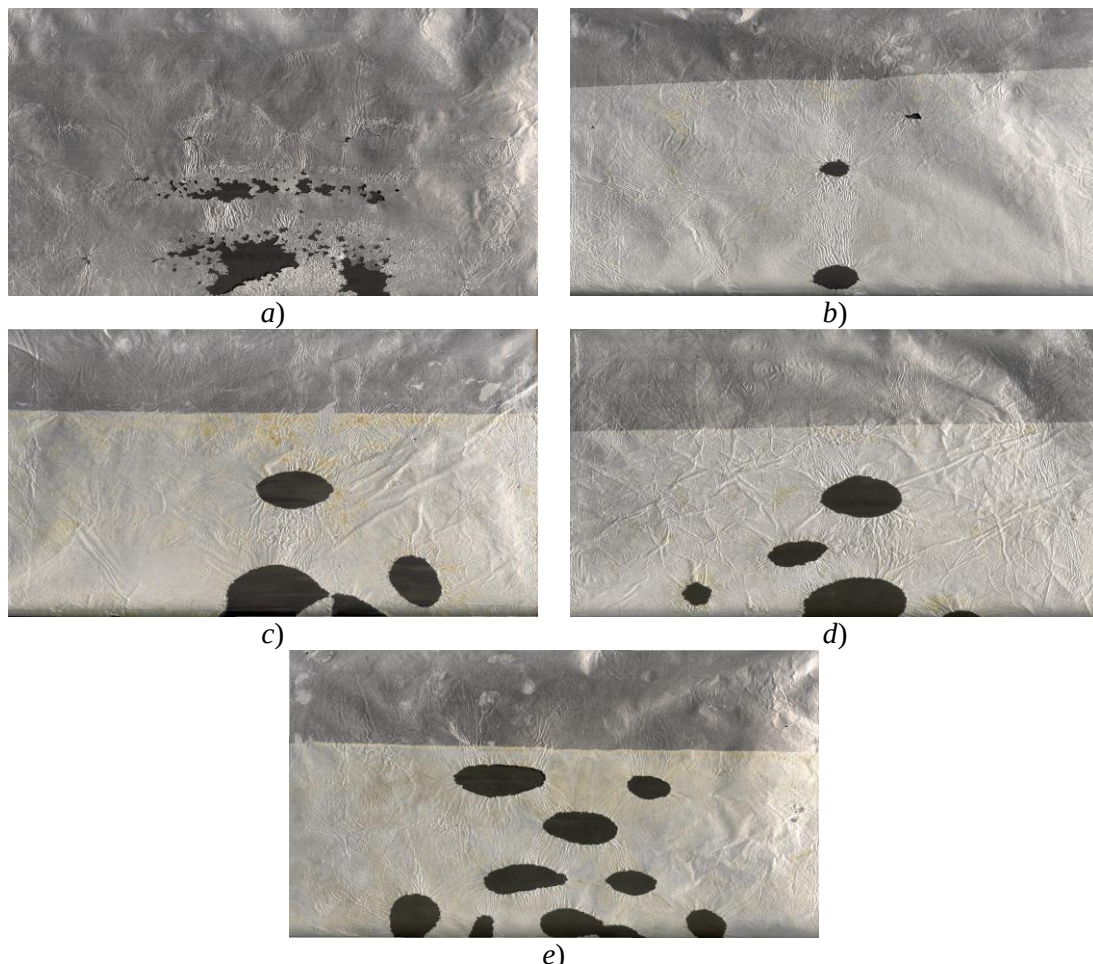


Figure 4. Photographs. Results of the first stage of the experiments.

- a) Cavitation time 10 min., drinking water, at $t = 13^{\circ}\text{C}$.
- b) Cavitation action time 10 sec., industrial wastewater, at $t = 38^{\circ}\text{C}$.
- c) Cavitation action time 1 min., industrial wastewater, at $t = 38^{\circ}\text{C}$.
- d) Cavitation action time 5 min., industrial wastewater, at $t = 38^{\circ}\text{C}$.
- e) Cavitation time 10 min., industrial wastewater, at $t = 38^{\circ}\text{C}$.

Cavitation destruction (erosion) is recorded as holes in the central part of the canvas.

The degree of change in the physicochemical properties of water affects the intensity of the cavitation regime in the ultrasonic field. Thus, in a sample of sewage with a high degree of change in the physicochemical properties of water, the effect of cavitation action surpasses the similar effect in water of a lesser change in the physicochemical properties.

Thus, the resulting image on the canvas will help determine the location of the cavities of cavitation destruction and visually, with certain certainty, fix the cavitation mode in the test sample.

In the second stage, experimental data on the change in sound pressure were obtained. The developed device allowed to fix the cavitation pressure of the collapsing cavities at selected points of the reactor. The diagram of the isosurfaces of sound pressure distribution in the volume of the reactor is constructed from the points obtained (Fig. 5).

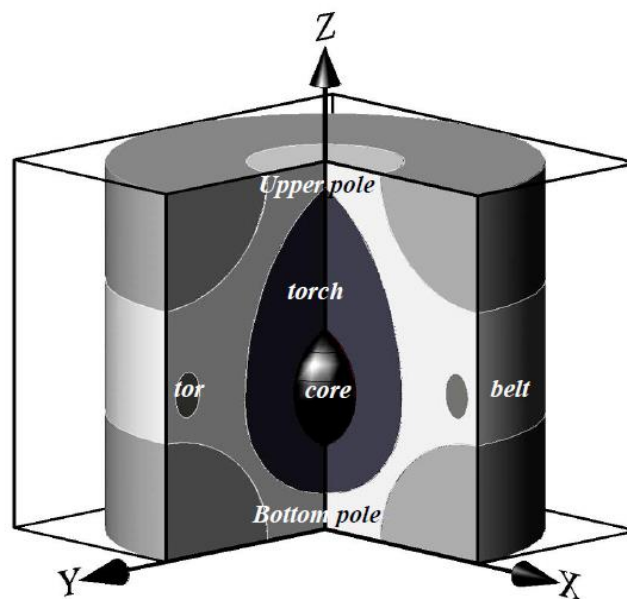


Figure 5. Diagram of acoustic pressure distribution in the volume of ultrasonic reactor in cavitation mode

The axonometric image makes it possible to comprehend the inhomogeneities of the zones of cavitation manifestations in the volume of the reactor. Thus, in the central part of the diagram there is a region of increased cavitation effect, reminiscent of the appearance of "torch" with a pronounced "core" of the maximum value of the acoustic pressure.

"Torch" is placed in suspension above the radiating membrane and its central part does not surface on the surface of the liquid medium.

The central part of the diagram is very similar to the "yule" and is characterized by a region of lower acoustic pressure than the central part of the "torch", which corresponds to the physical parameters of the process: the length of the acoustic wave, the frequency and the radiation intensity. Nevertheless, in the central part of the diagrams around the perimeter, at the level of "core", a region of concentrated energy was formed, in the form of "torus".

The energy saturation of the "torus" region is comparable to the "torch" region, but is substantially lower than the power of the cavitation manifestations than in the "core" region.

3. Solutions

1. The first stage of experimental studies made it possible to obtain real confirmation of ultrasonic cavitation in a liquid medium in the volume of the reactor.
2. In the second stage of the experiments, the points of the maximum and minimum cavitation regime propagating in the reactor volume were established and registered simultaneously.

4. Conclusion

The statement of the phenomenon of cavitation in a liquid medium with the use of erosive characteristics of an artificial obstacle is a simple and reliable way of recording this physical process. On the basis of a visual representation of the zones of cavitation manifestation, it is possible to substantiate the design parameters of the reactor, depending on what effects are required to be obtained in a liquid medium under the action of an ultrasonic field in the cavitation regime.

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