

# Estimation of efficiency of ultrasonic cavitation processing of technological media on energy criteria

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**Abstract.** The paper presents the energy evaluation of cavitation treatment of technological environments with the aim of establishing such parameters that implement the optimal conditions to maximize the transfer of energy to the stages in cavitation generation, development and slam shut bubbles. Accounting multiple transformation of energy of ultrasonic vibrations, as the need to improve the efficiency of the process based on the gradual definition of qualitative and quantitative picture of the energy in the contact zone of cavitation and technological environment and conditions of transfer of energy to the technological environment. Definition and consistent calculation of the energy conversion chain for the implementation of this idea used existing and developed new criteria for evaluating methods of acoustic treatment of technological environments: the intensity, the ratio of energies, a synergistic coefficient, coefficient of energy absorption, the rate of change of pressure in time; the wave resistance of the medium in the regimes of cavitation resistance of the initial state of the environment and others. This approach, as the process of improving existing or establishing new systems and technologies is synergistic systems. On the basis of research and evaluation of these criteria formulated synergistic principles of perfecting of conditions and parameters of the system “ultrasonic installation – technology environment”.

**Keywords:** technological environment, ultrasonic cavitation, processing stages, energy, evaluation criteria, synergetic principles

## Introduction

Cavitation technology occupies a prominent place in a number of advanced and effective methods of processing different environments and the creation of new materials. The uniqueness and efficiency of this technology is due to the formation of cavitation vapor bubbles in the process medium, which accumulate energy when they expand in one half-cycle of ultrasonic vibrations and form shock waves and cumulative jets when compressed in another half-period. Shock waves cause changes in the structure and properties of technological environments, increase the interfacial interaction surface, implement dispersion, dissolution, emulsification and many other processes.

Modern development of technology is due to the search for solutions to increase the efficiency of ultrasonic effects on chemical processes and reduce energy costs. These two tasks are based mainly on two areas of research: the establishment of physical and mathematical models that most closely reflect the real process and the identification of ways to intensify the process.

Despite the speed of the cavitation process, most research results indicate the presence of the following stages: pre-cavitation, nucleation, development, flattening, degenerate cavitation. It is obvious that the assessment and definition of rational energy distribution, as the main factor in the efficient course of these stages and is the solution of the above problems. The main problem in creating the conditions for the implementation of the maximum direction of energy flows is that the acoustic apparatus, as an energy source and technological environment, as its consumer, have fundamentally different properties and their manifestation in interaction with each other. The solution to this problem is to determine and consistently take into account the multiple energy conversion of ultrasonic vibrations based on the

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assessment of qualitative and quantitative picture of energy production in the contact zone and the conditions of energy transfer to the technological environment.

To determine and consistently calculate the stages of energy conversion in the work used existing and developed new criteria for evaluating methods of acoustic processing of technological environments: intensity, energy ratio, synergetic coefficient, energy absorption coefficient, rate of pressure change over time; wave resistance of the medium in cavitation modes to the resistance of the initial state of the medium and others. According to this approach, synergetic principles of improving the modes and parameters of systems “ultrasonic installation – technological environment” are formulated.

## Literature Review and Problem Statement

A number of works are devoted to the study of the energy of ultrasonic cavitation action on the technological environment. Thus, in [1], a parameter is given that determines the energy density  $A_k / V_k$ , where  $A_k$  is the work performed by all bubbles of the cavitation volume  $V_k$  of maximum radius  $R_m$  when they are closed. The graph of energy density  $A_k / V_k$  as a function of  $\tau \approx 0.5 T$  ( $\tau$  is the bubble burst time;  $T$  is the bubble oscillation period) shows that the maximum corresponds to the condition  $\tau \approx 0.5 T$ , when cavitation bubbles have time to close in  $0.5 T$ . The influence of the parameter  $R_{\max} / R_0$  on the efficiency of closing the bubble also follows from the simple energy considerations given in [2], which states that in the expansion phase the bubble acquires potential energy.

In [3], the dependences of the energy flux density transmitted by the wave and the energy density of the ultrasonic field in this region, known from acoustics [4], were used. The value of the speed of sound propagation in the cavitation medium was obtained by comparing these dependences. However, determining the energy flux density transferred through the cavitation medium and the energy density in the cavitation medium itself requires fixing the numerical value of the medium density and the pressure in the area of bubble cavitation. In addition, the dependences for determining the energy flux density carried by the wave and the energy density of the ultrasonic field in this area need to be supplemented by taking into account the dissipative properties of the medium and fixing a certain stage of the cavitation process.

Confirmation of the influence of viscosity on the cavitation process is indicated in [5 – 8]. In [5] it was noted that the force acting on the bubble depends not only on the parameters of motion at a given time, but also on how the bubble moved some time before. That is, the so-called effect of “memory possession”, which occurs in a viscous environment. The viscosity causes the local currents caused by the movement of the bubble to gradually fade. But this does not happen instantly, which means that these currents will have time to affect the future movement of the bubble. In [6], a certain effect of viscosity on the gradual motion of the bubble was noted and it was noted that “the dissipation of kinetic energy is completely restored due to the potential, which turns into kinetic energy when the cavity is compressed”. Not quite correct statement about the dissipation of kinetic energy. [7] also notes the effect of viscosity on the process in terms of the possible loss of the spherical shape of the bubble due to the presence of viscosity forces. The results of the influence of media with high viscosity are given in [8]. However, these results are based on constant parameters without possible change in the process of ultrasonic treatment of process media. The importance of impulse action on the technological environment is noted.

Significant results in the direction of the use of pulsed energy are given in [9]. At a pressure pulse  $P(t)$  close to the rectangular ( $\tau \rightarrow 0$ ) energy of external forces, the transmitted gas in the bubble in an ideal liquid is assumed to be equal to:  $E = P_m \cdot \Delta V$ , where  $\Delta V$  is the change in the volume of the bubble. If the amplitude of oscillations is large, ie ( $R_0, R_{\min}$  – the initial and minimum radii of bubbles), then the expression for determining the energy will look like:

$$E = \frac{4}{3} \pi R_0^3 P_m.$$

The mass of gas in the bubble at a given equilibrium pressure is proportional to the initial volume of the

bubble, and the density of energy stored in the bubble under accepted conditions does not depend on its initial radius. In other words, the maximum gas temperature in the adiabatic case (with the instantaneous application of external pressure) does not depend on the initial radius of the bubble, but depends only on the value of the applied pressure. In fact, taking into account the speed of sound at the final stage of processing the medium is the expansion of the front of the pressure shock pulse, resulting in higher values of thermodynamic parameters are achieved inside the bubble with a large initial radius [9]. A certain share of the energy of the primary sound field, which is spent on the formation of the cavitation region, is also mentioned in [10], where the results of the study of pressure change as a key energy parameter are presented. An important aspect of this result is the confirmation that it is impossible to increase the volume of the cavitation region and the concentration of cavitation bubbles in it at a given energy level and fixed oscillation parameters.

The ambiguity of the influence of viscosity on the cavitation process of processing the technological environment indicates the need for such an assessment, as evidenced by the results of [11, 12]. In [11] it was found that the

determining influence on the optimal modes of the technological process and the conditions of oscillation propagation have rheological properties. In this case, the functions of converting electrical energy into energy of acoustic oscillations and radiation of energy into the working medium must be such that the radiator provides the most efficient introduction of energy into the working medium in coordination with the resistance forces of this medium. In [12] the structural and phenomenological approaches to the establishment of the stress-strain state of cavitation processing of technological media are determined. It is necessary to choose such a calculation model, which describes with sufficient accuracy the processes occurring at all stages of the movement of the ensemble of bubbles.

The process of energy dissipation in dispersed media according to [13] can be described by a multidimensional stochastic model. Noting the complexity of using such a model to calculate energy, in the cited work [13] it is proposed to use the relationships between stress and strain based on the Rittinger hypothesis, widely known as the theory of material grinding, which declares the formation of new surfaces under external load. It is believed that this theory can be successfully applied to grind fine material (eg, cement) with a degree of grinding:  $i = D/d = 250$  and more ( $D$  is the size of the input fraction;  $d$  is the size of the output fraction). The author of [13] determined the energy for grinding emulsion particles on the example of cow's milk with initial numerical values of particles with a diameter of 1 ... 20  $\mu\text{m}$  to 0.1, 0.5 and 0.7  $\mu\text{m}$ . Without focusing on the analysis of the results and the possible validity of this theory for cavitation processes, we can note the following. In [14] it is noted that the disadvantage of Rittinger's theory is that only surface energy is taken into account for the deformation of the material. Therefore, it is obvious that this theory does not take into account the physical aspects of the process of cracking even solid homogeneous materials without comparing dispersed multiphase systems. After all, the process of grinding them is accompanied by the presence of a large number of other properties and factors of the technological process.

Thus, as a result of the analysis of literature sources, the following can be noted. Little attention is paid to the laws of change of rheological properties of technological environments in the process of their processing and the need to assess and take into account these changes in practical calculations. The interaction of the cavitation apparatus and the technological environment, which should be taken into account when determining the energy, rational parameters and process modes, has not been fully considered. There are no fundamental studies on the search for conditions for the conversion of electrical energy into energy of acoustic oscillations in terms of optimizing the radiated energy into the working environment. Not fully known criteria reflect the assessment of the energy of the structured system "ultrasonic installation – technological environment". Evaluation of the qualitative and quantitative picture of energy formation in the contact zone and conditions of rational energy transfer opens the way to develop synergetic principles of improving the modes and parameters of the systems "ultrasonic installation – technological environment".

### **The purpose and objectives of the study**

The aim of the work is to develop new and improve the known criteria for evaluating the effectiveness of modes and parameters of the working process of the system "ultrasonic installation – technological environment".

Objectives of the study:

- substantiation of the model of the system "ultrasonic installation – technological environment" for the development of criteria for evaluating the effectiveness of the stages of the cavitation process;
- development of new and improvement of existing energy criteria;
- determination of parameters of energy criteria.

### **Research methods for evaluating the effectiveness of ultrasonic cavitation processing of technological media by energy criteria**

The research methodology for assessing the effectiveness of ultrasonic cavitation on technological environments is based on the use of the results of their own work [15 – 17] and the corresponding analysis of the work of other authors [18, 19]. In [15] approaches to determining the model and parameters of the process of cavitation of the technological environment are considered. It was found that the technological environment, subject to cavitation processing, is an elastic-viscous-plastic body and can be described by the Bingham-Shvedov model. The idea of considering the contact zone of interaction of the system "cavitation apparatus – technological environment" on the basis of determining the balance of force pressure of the apparatus and stresses arising in the surrounding bubbles with the model of fluid as a system with distributed parameters. Analytical dependences for the establishment of basic parameters, including contact pressure and impedance in the contact zone of the system "cavitation apparatus – technological environment" are obtained. These results are the initial information, because the model is defined and analytical dependences are obtained to establish the main parameters, including contact pressure and impedance. In [16] the research of the previous [15] in terms of determining the structural and phenomenological approaches to the establishment of the stress-strain state of technological environments is expanded. This is a new result, because for the

first time two physical-mathematical models of treated media with frequency-dependent and frequency-independent laws of change of dissipative properties are considered. Analytical dependences are obtained for these two laws and regularities of change in layers of technological environment of dynamic pressure which are one of the main parameters for formation of criteria of an estimation of parameters of influence on formation and establishment of a cavitation field in a contact zone are established. The importance of [17] is that it defines a method for measuring the configuration of the cavitation region and the intensity of cavitation processes using hydrophones. The constructed graphs made it possible to evaluate the cavitation process of processing technological environments. The energy of the cavitation process, as a methodological tool for developing criteria for evaluating efficiency is disclosed in [18], which developed the approach [19] in terms of the impact of energy balance components on the spraying process:

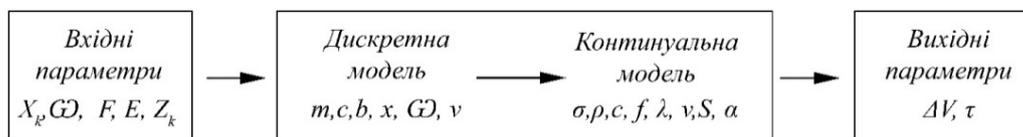
$$E_{c.w} = E_{sup} - E_{cav} - E_{v.f} - E_{g.m}, \quad (1)$$

where  $E_{c.w}$  – ultrasonic energy to excite a standing capillary wave on the surface of the liquid layer;  $E_{cav}$  – energy for the formation of the cavitation zone;  $E_{v.f}$  – energy to overcome the viscous friction in the fluid layer;  $E_{g.m}$  – energy radiated from the surface of the liquid into the gaseous medium.

Assuming that the longitudinal wave of deformation in the acoustic system of the disperser is flat, the components of equation (1) are determined. Numerical simulation of the capillary-wave sputtering regime showed that the energy losses to create a cavitation zone under different input influences and external conditions are 0.01–0.05 % of the supplied energy. In the cavitation mode of spraying, these losses reach almost 10 % [18].

## Research results

**Substantiation of the model of the system “ultrasonic installation - technological environment” for the defined criteria of efficiency of stages of cavitation process.** The step-by-step application of the transition model from a discrete to a continuous type is used as a basis for determining the criteria for evaluating the effective modes and parameters of the working process of acoustic processing of the technological environment (Fig. 1).



**Fig. 1.** Block diagram of the model that reflects the process of acoustic processing of the technological environment

It is assumed that the mathematical expressions of the criteria must be reliable to real conditions, to reflect the processes of bubble formation, their development, the formation of the cavitation region of bubbles of maximum volume and the stage of their flattening. The transition from the motion of a single bubble (discrete model) to the flattening of a large number of them (cavitation region, continuous model) in the description of the process is due to their importance. The first level considers the physics of the formation and determination of the radius of a single cavitation bubble  $R$  from time  $t$ , the intensity of ultrasonic vibrations  $I$  and rheological properties of the medium, in particular density  $\rho$ , viscosity coefficient  $\nu$ , modulus of elasticity  $E$  taking into account rheological properties:  $R = f(t, I, \rho, \nu, E)$ .

The established dependence of the radius of the cavitation bubble is a prerequisite for determining the average level of detail of the model of the formation of the cavitation region. The implementation of this level of research is the analytical dependence with certain refinements of the numerical values of the acoustic parameters of the environment and the apparatus. Due to this, the permissible range of numerical values of the intensity of ultrasonic oscillations is set, in which the bubbling is realized. The next prerequisite for research is the average level at which the set of cavitation bubbles in the region with dimensions  $L$ , which are smaller than the ultrasonic wavelength  $\lambda$ , but are much larger than the radius of the cavitation bubble  $R_b$ :  $\lambda \gg L \gg R_b$ . This condition makes it possible to establish the dependence of the volume content of cavitation bubbles  $V_b$  and their concentration  $n_b$  on the intensity of ultrasonic oscillations  $I$ , time  $t$  and rheological properties of the liquid  $\rho$ . At the third level, the total volume and shape of the cavitation area is determined, the intensity of ultrasonic action is set, which provides the conditions of the intensive mode of developed cavitation, as the final stage of the technological process. Thus, based on the above, the dominant influence on the sequence of the cavitation process is carried out by the following acoustic parameters and properties of the environment:

$$F = f\{A, A_i, f, v, W, P, L, t, l, p, \sigma, c, E, \rho, \mu\}, \quad (2)$$

where  $F$  is the functional (integral criterion for evaluating the process);  $A$  – amplitude of oscillations of the contact zone “acoustic apparatus – environment”;  $A_i$  – current amplitude of oscillations of the medium at a distance  $x_i$  from the boundary of the contact zone “acoustic apparatus – medium”;  $f$  – oscillation frequency of the acoustic apparatus;  $v$  – the oscillation speed of the contact zone “acoustic apparatus – environment”;  $W$  – energy,  $P$  – power;  $L$  – intensity;  $t$  – time,  $l$  is the characteristic size of the medium in the direction of propagation of the acoustic wave;  $p$  – pressure on the environment;  $\sigma$  – stress in the medium;  $c$  is the speed of propagation of the acoustic wave in the environment;  $E$  – modulus of elasticity of the medium;  $\rho$  is the density of the medium;  $\mu$  – is the coefficient of viscosity of the medium.

The integral parameters of function (2) are energy, intensity, power, which are the key parameters of the criteria for evaluating the efficiency of the technological process.

Development of new and improvement of existing energy criteria for evaluating the efficiency of ultrasonic cavitation treatment of technological media. The definition of energy criteria for evaluating the effectiveness of cavitation processing of the technological environment is as follows. Common to any cavitation process of processing the process environment is that the external energy of the cavitator  $A_k$  can be represented by the product of the useful power of the cavitation apparatus  $P$  ( $kW$ ) at the time of its use  $dt$  (c):

$$A_k = kPdt, \quad (3)$$

where  $k$  is the efficiency of the cavitator.

To determine the energy consumed during the cavitation process, its general expression is obtained on the basis of the imagination of the physics of the process, in the form of the product of specific energy ( $J/m^3$ ) required to obtain a certain volume of cavitation medium  $\Delta V(m^3)$ :

$$A_c = E_c \Delta V \quad (4)$$

Equation (4) is an indicator of the energy expended on the formation of the required energy level of the cavitating volume of the process medium.

Now you can record the energy balance of the system “cavitator – environment”:

$$kPdt = E_c \Delta V. \quad (5)$$

The physical essence of the parameter  $E_c$  is that it determines the level of energy that is absorbed by a particular medium in accordance with the summed level of external energy. This parameter is a qualitative indicator of the process. With a change in the state of the environment, as well as a possible change in the operating parameters of the acoustic apparatus, the  $E_c$  index also changes. The volume index  $V_k$  is a quantitative indicator of the process. Assuming that  $V_k$  is the volume of those cavitation bubbles that close, and  $V_{d.o.}$  volume of non-slapping bubbles (long-lived bubbles), their ratio can be represented as a criterion of the applied parameters of acoustic treatment of the environment,  $K_o$ :

$$K_o = V_{d.o.} / V_k \quad (6)$$

Equation of energy balance (5) makes it possible to record in general form and the productivity of the process:

$$\Delta \Pi = \frac{kP}{E_c}, m^3 / c \quad (7)$$

From (7) it follows that productivity expresses the ratio of useful energy and energy expended per unit of process, in this ratio determines the processing speed of the environment. The  $k/E_c$  ratio in formula (7) determines the level of efficiency of the cavitation process. Estimation of the level of energy  $E_c$  spent on nucleation, development of cavitation bubbles, their flattening and is an estimation of a course of this or that technological process of processing of technological environment. In [20] it is noted that the characteristic size of the vapor-gas phase, as well as its volume, significantly affect the intensity of cavitation. Based on the results of [21, 22], where it is noted that the intensity of cavitation depends on the speed of cumulative microcurrents, which, in turn, are associated with the critical size of vapor bubbles. Thus, the energy criterion for assessing the efficiency of the process in time can be taken as the rate of change of energy  $dE$  in time  $dt$ :

$$K_e = \frac{dE}{dt} - > min, \quad (8)$$

Here  $E$  is the energy expended on the flow of acoustic processing of the technological environment;  $t$  is the time of acoustic processing of the technological environment.

The criterion for obtaining the maximum volume of the cavitation region of bubbles  $K_{ob}$ , taken the rate of change of volume  $dV$  in time  $dt$ :

$$K_{ob} = \frac{dV}{dt} - > \max. \tag{9}$$

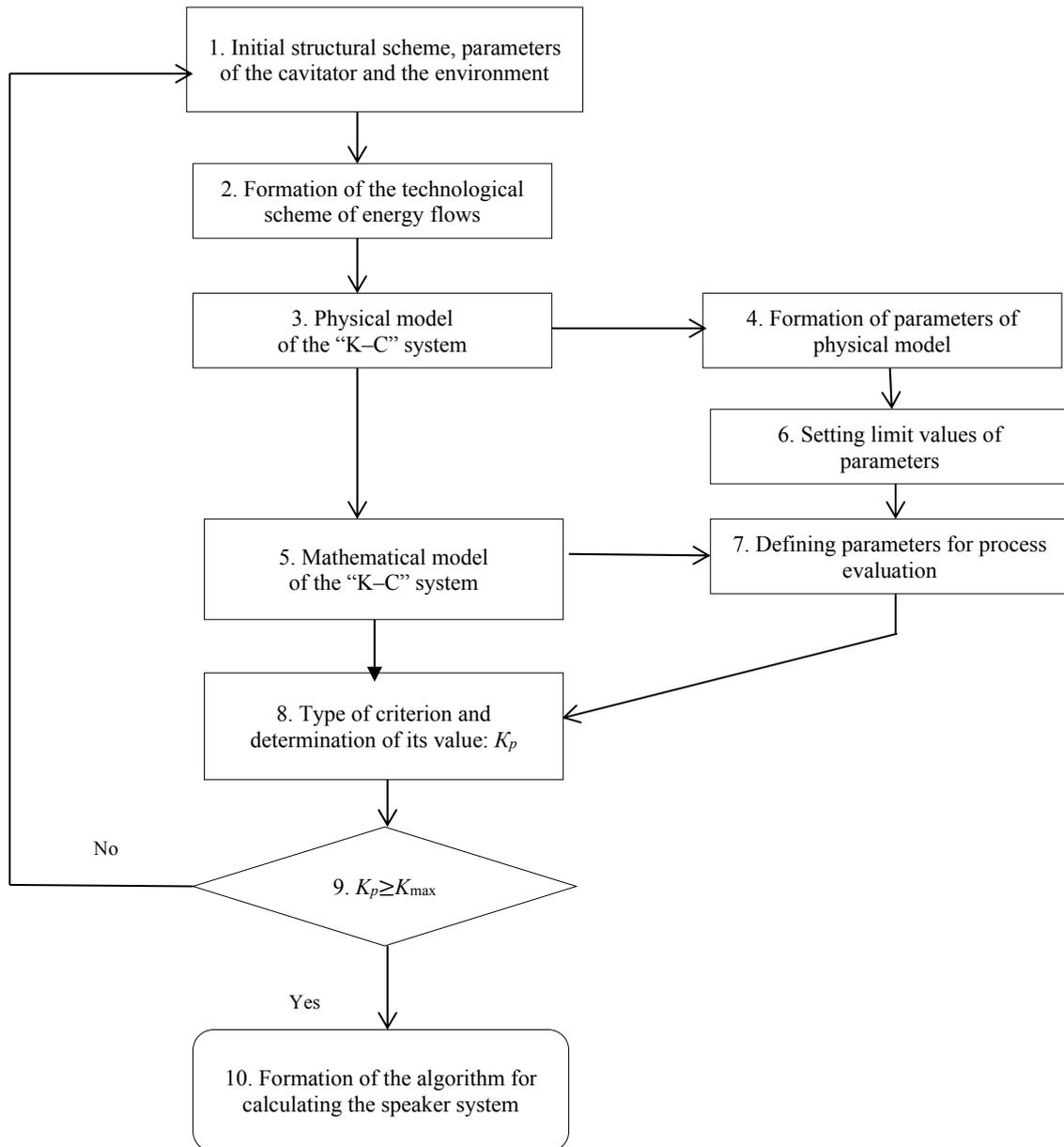
The energy released during the bursting of cavitation bubbles depends not only on the power of the acoustic radiation, but also on the bulk density of the acoustic energy. In addition to the energy index, information about the internal structure of the volume of the technological environment is taken into account: density, rheological properties, number of cavitation bubbles and their average size, the desired volume of cavitation bubbles as a component of productivity. On the basis of the conducted researches energy criteria of an estimation of efficiency of ultrasonic cavitation processing of technological environments are developed (tab. 1).

**Table 1.** Criteria and key parameters of energy assessment of the efficiency of the cavitation process of processing technological environments

№, п/п	Criterion, parameter	Analytical dependence
1	Intensity of cavitation process by type of oscillations	
1.1	Sinusoidal oscillations, W/cm <sup>2</sup>	$I = \frac{p^2}{2\rho c}; \quad I = A^2 \times f^3.$
1.2	Nonlinear (non-sinusoidal) oscillations, W / cm <sup>2</sup>	$I = \frac{\alpha \times A}{4\pi^2 T}.$
2	System synergy ratio (efficiency)	$k_c = E_c/E_{n,x}.$
3	Coefficient of transition of acoustic energy into energy of shock waves	$k_y = \eta \frac{E_y T}{E_k \tau}$
4	Coefficient of change of energy in time for all period of processing of bubbles, J/s	$\mu = 1/T(\ln E_0 / E_k)$
5	Energy absorption coefficient, m <sup>-1</sup>	$\kappa_n = P_{pit} / I.$
6	The ratio of the wave resistance of the cavitation medium	$k_{op} = \frac{\rho_k c_k}{\rho_c c_c} = \left[ \frac{1}{1 + \frac{K\beta_n}{\beta_0}} \right]^{1/2}$
7	Speed ratio	$\kappa_v = v_0 / c_k.$
8	The ratio of burst time to the period of oscillations	$\kappa_t = \tau / T.$
9	The specific energy of the volume of the cavitation medium, J	$A_c = E_c \Delta V$
10	Contact zone energy, J	$A_{kz} = \pi m_c x_0^2 \omega^2 \mu.$
11	Cavitator energy, J	$\bar{A} = \bar{P} \cdot t.$

Determination of parameters of energy criteria. To implement the criterion assessment of the rationale for the rational choice of the structural-parametric system “acoustic apparatus – technological environment”, an algorithm is proposed (Fig. 2).

The essence of the algorithm is the ability to vary not only the initial parameters and layout of the cavitator relative to the processing medium, but also to determine the influence of variable parameters on the maximum value of a criterion (Table 2). Depending on the problem, the criterion is selected, which is fixed in block 8. Later in block 2 “Formation of the technological scheme”, preliminary calculations are made on the mode of energy transfer to the environment in accordance with the selected criterion. An important step of the algorithm are blocks 3 and 5, which determine the physical and mathematical models, based on the performed and the above research results. In blocks 4, 6, 7 the initial data are formed to determine the numerical values of the parameters of influence and the limits of their rational use. Completion of the calculation are the parameters that serve as the source information for the final decision-making to improve the rational design and technological parameters of the acoustic cavitator.



**Fig. 2.** Scheme of criterion assessment of substantiation of rational choice of structural-parametric system “acoustic device – technological environment”

This technology of the proposed algorithm is a fundamentally new system of automatic parameter search to meet the condition of providing the criterion of block 9. For example, criterion 5 (Table 1) represents the relationship between the intensity  $I$  of specific energy  $P_{num}$  and energy absorption coefficient:

$$\kappa_n = P_{num}/I. \quad (10)$$

On the other hand, the product of the specific energy required to obtain a certain volume of cavitation medium  $\Delta V$  in accordance with the dependence (3)

$$A_c = E_c \Delta V \cdot I. \quad (11)$$

Then we have that the specific energy  $P_{num} = I \cdot \kappa_n$ . Equating  $P_{num} = E_c$  we obtain

$$A_c = \kappa_n I. \quad (12)$$

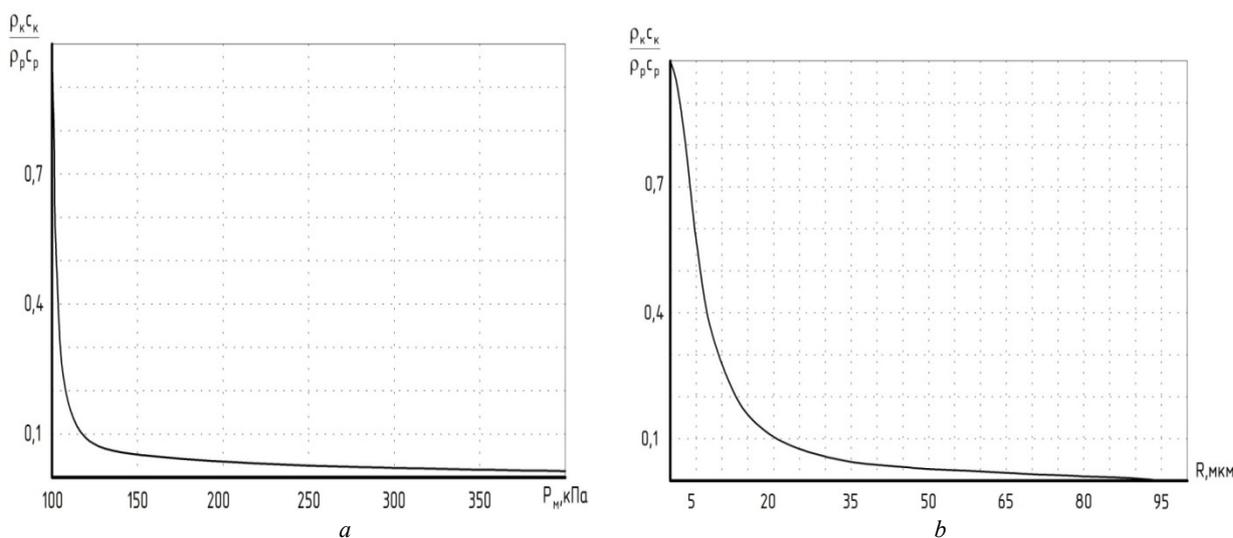
Thus, the energy absorption coefficient  $kp$  not only characterizes the change in the specific energy  $P$  demand and the intensity of ultrasound  $I$  in the irradiated medium, but also serves as a criterion for evaluating the efficiency of the

process of acoustic treatment of this medium. One of the dominant parameters of the criteria for energy evaluation of the technological process is the intensity, the limit values significantly depend on the viscosity (Table 2).

**Table 2.** Intensity limits for media of different viscosities

Viscosity, $\eta, 10^{-3}\text{Pa}$	20	40	80	100	150	250	300	400
Intensity, $I_{\min}, \text{W/cm}^2$	1,75	2,00	2,45	2,55	3,75	7,50	12,50	16,00
Intensity, $I_{\max}, \text{W/cm}^2$	4,35	6,00	7,55	7,75	10,35	17,00	21,55	35,00

The ratio of the wave resistance of the cavitation medium (criterion 6, Table 1) reflects the degree of change in the process (Fig. 3 a, b).



**Fig. 3.** Changing the ratio of the wave resistance of the cavitation medium (*a* – depending on the external pressure, *b* – depending on the radius of the bubble)

Determination of other parameters of the cavitation process, which are part of the criteria are the amplitude of oscillations, viscosity of the medium, the maximum radius of the bubble, the surface tension of the bubble (Table 3), the sound pressure, the ratio of the radii of the bubble ( $R_{\max} / R_0$ ) (Table 4).

**Table 3.** The relationship between the amplitude of oscillations, viscosity and the maximum radius of the bubble

Amplitude of oscillations, microns	4,0	12,0	20,0
Viscosity, $10^{-3} \text{ Pa} \cdot \text{c}$	1,0	30,0	50,0
The maximum radius of the bubble, microns	35,0	48,0	60,0
Surface tension of the bubble, $10^{-3} \text{ N / m}$	1	72	150

**Table 4.** The dependence of the maximum radius of cavitation bubbles on the value of sound pressure

The magnitude of the sound pressure, $10^3 \text{ Pa}$	500	1000	1500	2000	2500	3000
The ratio of the radii of the bubble, $R_{\max} / R_0$	160	270	350	420	460	520

**Discussion of the results of the study of the evaluation of the efficiency of ultrasonic cavitation treatment of technological media by energy criteria.** The results of research indicate the acquisition of new criteria and improvement of known ones. In the given table criteria and key parameters are resulted in sequence of realization of an estimation of possible modes and efficiency of cavitation process of processing of technological environments. The main set of criteria involves assessing the energy of the process, both the key characteristics and

taking into account possible changes in key parameters from the stage of bubble formation to the final stage – bubbling. Extremely important are the criteria that directly determine the reliability of the choice of mode (harmonic or pulse mode). The energy absorption coefficient (criterion 6) not only characterizes the change in the specific energy  $P$  demand and the intensity of ultrasound  $I$  in the irradiated medium, but also serves as a criterion for evaluating the efficiency of the process of acoustic treatment of this medium.

The proposed algorithm is a fundamentally new system of possible automatic parameter sorting to fulfill the condition of providing a particular criterion. The second important aspect of this algorithm is the creation of a control system for the process of processing objects with an ultrasonic cavitation unit in the optimal mode of its operation. This is a fundamentally new result. This requires the development of a control scheme for the structural-parametric system “acoustic apparatus – technological environment”. Such studies are planned as a continuation of the results of this topic.

## Conclusions

1. Models of the system “ultrasonic installation – technological environment” for development of criteria of an estimation of efficiency of stages of cavitation process on the basis of consecutive transition from movement of a single bubble (cavitation origin, discrete model) to flattening of ensemble of bubbles (cavitation area, continuous model) are defined.

2. New and improved known energy criteria and key parameters are developed, which are given in the sequence of assessment of possible modes and efficiency of the cavitation process of processing technological environments. The main set of criteria involves assessing the energy of the process, both the key characteristics and taking into account possible changes in key parameters from the stage of bubble formation to the final stage – bubbling.

3. Defined parameters of energy criteria, which open the ability to automatically sort the parameters to ensure a particular criterion. The proposed algorithm is a prerequisite for creating a control system for processing objects with an ultrasonic cavitation unit in the optimal mode of its operation.

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## Оценка эффективности ультразвуковой кавитационной обработки технологических сред по энергетическим критериям

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**Аннотация.** В работе проведена оценка энергетики кавитационной обработки технологических сред с целью установления таких параметров, которые реализуют оптимальные условия создания максимальной области передачи энергии на стадиях зарождения кавитации, развития и захлопывания пузырьков. Учет множественного превращения энергии ультразвуковых колебаний, как необходимость повышения эффективности процесса, основанном на поэтапном определении качественной и количественной картины образования энергии в зоне контакта кавитационного аппарата и технологической среды, и условий передачи энергии к технологической среде. Определение и последовательное вычисление этапов преобразования энергии для реализации такой идеи использованы существующие и разработаны новые критерии оценки методов акустической обработки технологических сред: интенсивность, соотношение энергий, синергетический коэффициент, коэффициент поглощения энергии, скорости изменения давления во времени; волнового сопротивления среды в режимах кавитации к сопротивлению начального состояния среды и другие. Такой подход, как процесс совершенствования существующих или создания новых систем и технологий, является синергетическими системами. На базе исследований и оценки указанных критериев сформулированы синергетические принципы совершенствования режимов и параметров систем “ультразвуковая установка – технологическая среда”.

**Ключевые слова:** технологическая среда, ультразвуковая кавитация, стадии обработки, энергия, критерии оценки, синергетические принципы.

## Оцінка ефективності ультразвукової кавітаційної обробки технологічних середовищ за енергетичними критеріями

І. М. Берник

**Анотація.** В роботі здійснена оцінка енергетики кавітаційної обробки технологічних середовищ з метою встановлення таких параметрів, які реалізують оптимальні умови створення максимальної області передачі енергії на стадіях зародження кавітації, розвитку і сплескування бульбашок. Врахування множинного перетворення енергії ультразвукових коливань, як необхідність підвищення ефективності процесу, ґрунтувалося на поетапному визначенні якісної та кількісної картини утворення енергії в зоні контакту кавітаційного апарату і технологічного середовища та умов передачі енергії до технологічного середовища. Визначення та послідовне вираховування етапів перетворення енергії для реалізації такої ідеї використані існуючі та розроблені нові критерії оцінки методів акустичної обробки технологічних середовищ: інтенсивність, співвідношення енергій, синергетичний коефіцієнт, коефіцієнт поглинання енергії, швидкості зміни тиску у часі; хвильового опору середовища в режимах кавітації до опору початкового стану середовища та інші. Такий підхід, як процес вдосконалення існуючих або створення нових систем і технологій, являється синергетичними системами. На базі досліджень та оцінки зазначених критеріїв сформульовані синергетичні принципи вдосконалення режимів та параметрів систем “ультразвукова установка – технологічне середовище”.

**Ключові слова:** технологічне середовище, ультразвукова кавітація, стадії обробки, енергія, критерії оцінки, синергетичні принципи.

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