Фізика аеродисперсних систем. – 2023. – № 61. – С.227-240

UDK 532.528+534.29

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Some problems of modeling the liquid cavitation degassing. I. Acoustic cavitation

In recent decades, cavitation methods of liquid degassing have become widely used, which today have practically replaced the traditional time-consuming mechanical and chemical methods of degassing in industry. The application of cavitation methods is based on the fact that a part of the neutral gases present in the liquid is not in a dissolved state, but in a so-called "free" state in the composition of a large number of vapor-gas bubbles, the size of which is measured on the scale of micro- and nanometers. The nature of the stable, long-term existence of such micro-bubbles has not yet found a reasonable explanation and is the subject of debate among researchers. Cavitation methods of degassing, both hydrodynamic and acoustic, are aimed precisely at the rapid removal of these bubbles from the liquid together with the free gas present in them. The advantage of using acoustic cavitation methods is the ability to precisely control the frequency and intensity of ultrasound, as well as the duration of sounding. Acoustic degassing methods are based on two mechanisms: the passage of dissolved gas inside pulsating bubbles due to the effect of "directed diffusion" and the convergence and subsequent coalescence of neighboring bubbles under the influence of force Bjerknes As a result, the growing bubbles quickly float up and leave the liquid together with the free gas. In recent years, a large number of articles on the comprehensive study of acoustic degassing processes have been published. According to the authors of these publications, the mechanism of degassing at the microscopic level and all the diversity of bubble dynamics, depending on the frequency and intensity of the sound, remain unclear.

This article examines the main problems of modeling acoustic degassing processes, which confirm the absence of generally accepted clear ideas about the physical nature and mechanisms of cavitation phenomena and a general approach to the analysis of the obtained results. In order to develop research in this direction, the article also presents the results of a computational experiment on the coalescence of pulsating bubbles, conducted by the authors on the basis of a model of the dynamics of a single bubble previously created by them. As a result of the theoretical study, new, previously unknown information about the force interaction of pulsating bubbles of different sizes was obtained, which can be considered as a certain contribution to the understanding of the mechanisms of acoustic degassing.

Key words: *acoustic degassing, gas micro-bubbles, modeling, coalescence.*

Introduction. Technological processes of liquid degassing are used in various branches of industry - in chemical, food, oil processing, in energy, in water treatment processes and others. Traditional methods of extracting aggressive gases from the liquid, such as oxygen, carbon dioxide, hydrogen sulfide, etc., which are based on heating the liquid or vacuuming it, are too energy-consuming and inefficient due to

DOI: 10.18524/0367-1631.2023.61.292236

the small surface area of contact of the liquid with the surrounding gas environment. In recent decades, cavitation methods of degassing have become widely used, which today have practically replaced traditional methods in industry.

The use of cavitation methods to remove gas from a liquid is based on the fact that the neutral gas contained in the liquid is not only in a dissolved state, but also in the form of free gas inside micro-bubbles that are stably present in any liquid. Free gases contained in the liquid, such as O_2, CO_2, SH_2 are chemically more aggressive than the same gases in a dissolved state [1,2]. Present in ordinary water, they act as catalysts for corrosion processes

Cavitation degassing methods are aimed specifically at removing bubbles containing free gas from a liquid. The effectiveness of the method increases when degassing supersaturated liquids in which the content of gas exceeds the threshold of its solubility at a given pressure and ambient temperature in accordance with Henry's law [3-5]. If for some reason the equilibrium is disturbed and the liquid becomes supersaturated, excess gas from the solution quickly moves into the bubbles due to the developed phase contact surface.

Comprehensive studies of acoustic degassing of liquids have been intensively conducted since the second half of the last century. The experimental results confirmed the possibility of removing neutral gases from a liquid under ultrasound irradiation, but the mechanism of this phenomenon could not be properly explained.

Some researchers believed that degassing of a liquid is possible only after the formation of cavitation cavities under the influence of powerful ultrasonic (US) action, which then become degassing centers. According to others, degassing has nothing to do with cavitation, but is determined only by the diffusion of dissolved gas into pulsating bubbles already present in the liquid. An unambiguous answer to these questions was given in the fundamental works of Rosenberg [1] and O. Kapustina [6]. Based on a theoretical analysis of experiments known at that time, the authors of these works proved that acoustic degassing of liquids is an independent physical phenomenon not associated with cavitation, and that the centers of degassing are stable gas bubbles initially present in the liquid. In a certain range of intensities and frequencies, cavitation promotes the accelerated release of gas from a liquid, both by increasing the number of nuclei from which the process then develops, and as a result of intensifying mass transfer at the bubble-liquid interface.

Kapustina [6] conducted a thorough analysis of the experiments results on acoustic degassing (both her own and other authors) and came to the conclusion that there are two main mechanisms for removing gas from a liquid during its US treatment, namely: (1) - rectified diffusion of dissolved gas from a liquid into pulsating bubbles; (2) – convergence and merging of pulsating bubbles under the influence of the Bjerknes force and the subsequent ascent of the resulting large bubbles to the liquid surface. It was found that in the process of acoustic degassing, a maximum equilibrium level of dissolved gas is reached with $c^* \approx$ 70-50% of the saturated one ("pseudo-equilibrium"), the value of which, according to [6] does not depend either on the frequency or on the intensity of the acoustic fields. The presence of a limiting equilibrium concentration c^* is confirmed by the results of acoustic degassing experiments performed over the past decades. According to some researchers, this can be

explained by the existence of competing re-gassing processes that counteract the removal of gases, mainly due to the diffusion of gas from the atmosphere through the free liquid surface [7, 8].

To date, the results of studies of acoustic degassing are interpreted from the point of view of elucidating the role of each of these two factors. Most works on US degassing are devoted to a detailed study of the features of the processes of rectified diffusion both in an individual bubble and in a bubble cluster, and/or the coalescence of a set of bubbles. Over the past half century, following the publication of fundamental works [1,6], as part of numerous subsequent studies, a large amount of new useful information has been accumulated in the field of the physics of liquids, in particular water. Certain successes have been achieved in the field of studying the state and behavior of nano-sized gas dispersions in water, the nature of their unusual stability and longevity. At the same time, in the course of the research, a number of unexpected aspects were discovered that significantly complicate the understanding of the nature and mechanisms of acoustic degassing.

By definition, cavitation occurs when the pressure in a liquid decreases rapidly below the saturated vapor pressure ($p_l < p_{sat}(T_l)$), resulting in the formation and growth of bubbles, and then rapidly increases to a value $p_l > p_{sat}(T_l)$, leading to their compression and subsequent collapse. This definition applies equally to hydrodynamic cavitation, where the change in the liquid pressure is associated with the stretching and subsequent compression of the high-speed flow when passing through a narrow section of the channel, and to acoustic cavitation, where the drop and increase in pressure is due to periodic high-frequency stretching and compression of the liquid volume. From this point of view, acoustic cavitation methods using US sonication of liquids seem very promising. The possibility of controlled changes in the frequency and intensity of the US field over a wide range ensures the fulfillment of the conditions of cavitation - a rapid periodic change in pressure in the liquid within the specified limits. In relation to degassing problems, this makes it possible to justify optimal process modes based on productivity and energy efficiency criteria.

An experimental study of the gas bubbles dynamics in an US field is associated with obvious difficulties, given that the sizes of the objects under study lie in the range$10^{-2} - 10^{2}$ μm, and the variation in the size, shape, and location of these dispersions during the oscillation period is estimated on a nanosecond scale. Despite advances in the creation of precision measurement methods (infrared spectroscopy, nuclear magnetic resonance, etc.), the experimental data known today are often very contradictory, which makes it difficult to create unified mathematical models that can adequately predict the behavior of bubbles in relation to acoustic degassing problems.

According to the authors of recent publications, we still do not have enough knowledge to understand the full diversity of bubble dynamics, depending on the frequency and intensity of sound [9]. US degassing still poses some mysteries. Both the microscopic processes and the macroscopic description of the removal of gas from a liquid using ultrasound remain almost unexplored. In the same system, various bubble dynamics occur simultaneously and high sensitivity to external parameters is found. [8]. The mechanism of the influence of degassing bubbles on the US field is

not fully understood, since bubbles strongly attenuate ultrasound, and the size distribution density of bubbles constantly changes over time due to fragmentation, fusion and dissolution. [10]. First of all, this is the problem of poor reproducibility of some experimental results, which is usually associated with uncontrolled changes in the structure of water [11].

There is another problem associated with understanding the physical nature of US degassing. In any liquid there are a huge number of stable vapor-gas microbubbles, the distribution density of which in size $n_i(R)$ is estimated from the ratio $n_i(R) \propto A/R^3$ [1,2,8]. To activate bubbles - their unlimited and irreversible growth - the pressure in the liquid must be reduced to values $p_l < p_{sat}(T_l)$, as a rule, moving into the region of negative pressure ($p_l < 0$) due to stretching of the liquid. When the pressure decreases to a critical value $p_{cr}(R) < p_{sat}(T_l)$, which corresponds to the lower limit value of the radius of activated bubbles $R_{cr} = f(P_{cr})$, all bubbles with $R > R_{cr}$ are activated, and bubbles with $R < R_{cr}$ continue to be in a stable state.

To determine the boundary between two bubble behaviors in the parameter space $\langle p_{cr}, R_{cr} \rangle$, a quasi-static argument is used, the so-called Blake threshold [1,2,12], which determines the boundary of the transition from pre-cavitation to cavitation mode, that is, it separates stable pulsating bubbles ($R < R_{cr}$) from cavitation (inertial) bubbles ($R > R_{cr}$), which irreversibly expand with subsequent collapse. At a low intensity of the acoustic field $I_{ac} = p_{ac}^2 / 2\rho_l c_{ac}$, small bubbles can exist for as long as desired, performing weak pulsations at the field frequency f_{ac}. If the level of acoustic pressure $p_{ac} > p_{cr}$, these bubbles expand and collapse sharply within several periods of field oscillation, initiating characteristic dynamic effects - erosion of solid surfaces [4,5,13]., sonoluminescence, etc. [9,10,13, 15,16].

The purpose of this work is to conduct a brief analysis of the current state of the problems of liquid acoustic degassing, based on available sources of information and on the own results of the authors of this article. The rest of the article discusses the main mechanisms of acoustic degassing of liquids.

Rectified mass diffusion. During sonication in an US field, the bubble undergoes expansion and contraction. The pressure inside the bubble decreases as it expands and increases as it contracts. When the acoustic pressure exceeds a certain threshold, the bubble begins to grow, due to the effect of rectified diffusion - the uneven rate of mass transfer across the air-liquid interface. This uneven growth is explained by two effects: the “area” effect and the “shell” effect [15-18].

As the bubble expands, the surface area becomes larger and more gas enters the bubble than when the bubble contracts (the "area" effect). When the bubble is compressed, the thickness of the diffusion boundary layer increases, which reduces the gas concentration gradient in the layer, and when it expands, the opposite is true (the “shell” effect). According to Henry's law, more gas enters the bubble during expan-

sion than comes out during compression. In simple air-water systems, these two effects make the main contribution to the increase in rectified diffusion.

Krum [18] was the first to perform a detailed study of bubble growth in an acoustic field due to rectified diffusion under various US conditions. The experiment used the method of levitating a single bubble in a standing wave field to record changes in bubble size as a function of time. Using this method, Crum measured the growth rate of air bubbles in pure water and in water with small additions of surfactants ($2.5\cdot10^{-5} \div 3\cdot10^{-3}$ %) and refined the existing theory of rectified diffusion. When analyzing the experiment, Crum used Eller's equation [17] for the rate of bubble growth by rectified diffusion

$$\frac{dR}{d\tau} = \frac{D\cdot c_{rel}}{R}\left[\frac{0.25\cdot\left(3\delta\cdot p_0\right)^2}{3\delta\cdot\left(3\delta\cdot p_0 - \rho\omega^2 R^2\right)^2}\left(\frac{p_{ac}}{p_0}\right) + \frac{2\sigma}{R\cdot p_0}\right], \qquad (1)$$

where D – the gas diffusion coefficient in water; p_0 – atmosphere pressure; σ – surface tension of the liquid; c_{rel} – the ratio of the mass concentration of dissolved gas to the equilibrium concentration; ω – angular frequency; $\delta = 1$ for isothermal pulsations and $\delta = 1.4$ for the adiabatic case.

Crum's experimental results are in good agreement with theory [17] for simple air-water systems. However, this theory is unable to adequately predict the rate of bubble growth in water in the presence of colloidal ionic surfactants. In this case, the measured growth rates significantly exceed the predicted values. The reason for the strong influence of small surfactant additives on the bubble growth rate in the process of rectified diffusion, which is confirmed by other researchers [9, 14-16, 19, 20], remains unclear to this day, although there are certain prerequisites.

It is generally accepted that the increase in the growth rate of bubbles in the presence of a surfactant is explained by the slowdown in the diffusion of gas outward through the surface of the bubble. An important role is played by the packing density of surfactant molecules on the surface of the bubble. During expansion, the packing density decreases, which reduces the resistance to mass transfer across the interface. During compression, the packing density increases, increasing the resistance to mass transfer across the interface. As a result, a difference in mass flow is created, which leads to a net accumulation of gas in the bubble [15, 16].

The authors of [19] believe that an interfacial resistance is created on the surface of a pulsating bubble, depending on the surface concentration of surfactant molecules. The driving force is the non-equilibrium separation of gas into free and dissolved states at the interface, as a result of which the boundary conditions of Henry's law are not applicable.

In contrast to the large number of publications devoted to the theoretical study of rectified diffusion processes in relation to problems of acoustic degassing, the number of experimental studies on the growth of single bubbles by rectified diffusion is very limited. In addition to the fundamental work of Krum [18], two works [15,16] should be noted in which the stroboscopic method was used to record the growth of a single bubble in the field of a standing wave.

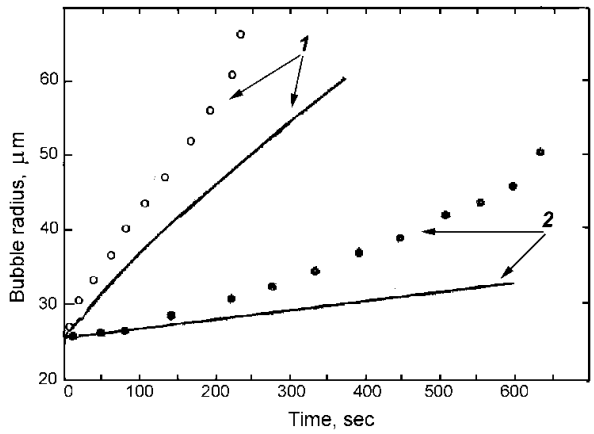

Fig.1. Variation of the bubble radius by rectified diffusion with time. R_0 =25·10^{-6} m; σ=3.2.10^{-2} N/m; f_{ac}=21,6 kHz; p_{ac}=0.36 bar (1) and p_{ac}= 0.20 bar (2). The circles are the experimental points and the curves are calculated from Eq.1. (Taken from Ref [18])

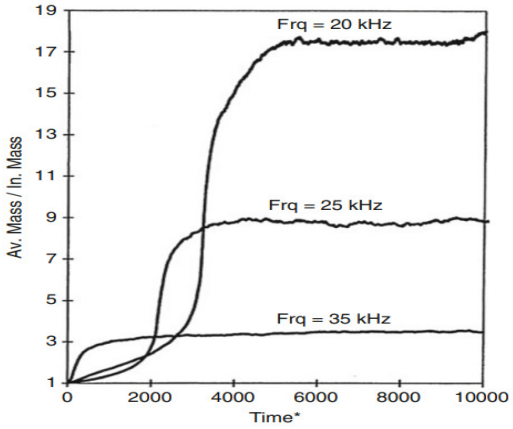

Fig. 2 Change in time of the average mass of gas contained in a bubble with a radial size of 70·10^{-6} m in the process of rectified diffusion for different frequencies of the acoustic field. (Taken from Ref [16])

As a result of complex studies, it has been established that the rate of growth of bubbles due to the entry of gas from the liquid depends significantly on various factors, such as the size of the bubble, gas concentration in the liquid, acoustic pressure and frequency of the US field, and the presence of soluble inorganic and/or organic components in the liquid.

The effect of acoustic pressure has been well studied, and there is complete agreement between experiment for pure water and theory. With increasing p_{ac} amplitude of the bubble pulsation increases, which ensures greater mass transfer per cycle and, accordingly, faster growth of the bubble (Fig. 1). When reduced p_{ac} to a certain threshold, which correlates with the Blake threshold, small-sized air bubbles irreversibly dissolve even in saturated water. This rectified diffusion threshold divides the parameter space into two parts: dissolving and growing bubbles [2, 9, 14, 15].

Research by [9, 14-16] has shown that the growth rate of rectified diffusion is inversely proportional to the US frequency. This is due to the decrease in the degree of bubble expansion with increasing frequency. Figure 2 shows that the gas mass acquired by the bubble during rectified diffusion decreases fivefold with increasing frequency from 20 to 35 kHz.

According to the experimental results of Krum and other authors, the rate of bubble radius change in the process of rectified diffusion is estimated on a scale of 10^{-8} m/s (0.01 μm/s). The growth of bubbles in the process of rectified diffusion is extremely slow compared to the growth of bubbles due to their coalescence. However, it provides a mechanism by which stable micro-bubbles can grow sufficiently to become cavitation nuclei. In this case, with an increase in the mass of gas in the bubble, the Blake threshold pressure increases and, therefore, a smaller decrease in pressure is required to create an unstable cavitation bubble. [2]

Imaging techniques used to study rectified single bubble diffusion are difficult to apply to multi-bubble systems due to competing processes such as bubble coalescence, which also influence the rate of bubble growth [9,13-16,20].

Growth of bubbles under the influence of the Bjerknes forces. In a multi-bubble US field, there are two acoustic forces responsible for the movement of bubbles or their approach. These are the primary and secondary Bjerknes forces.

The primary Bjerknes force, which is determined by the interaction of bubbles with the acoustic field, depends on the pressure gradient and the average vibration of the bubble per cycle. The Bjerknes force, averaged over time over the oscillation period $T = 1/f_{ac}$, which acts on a pulsating bubble under the influence of acoustic pressure $p_{ac}(x,\tau)$ is determined by the expression $F_{B1} = \left\langle V(\tau)\cdot\nabla p_{ac}(x,\tau)\right\rangle_T$, where $V = 4/3\cdot\pi R^3$; $p(x,\tau)$ and x is position of the bubble center [9, 13, 16].

In the field of a standing wave, bubbles are sorted by size. Bubbles with $R_0 > R_{res}$ are pressed against pressure nodes, and bubbles with $R_0 < R_{res}$ are pressed against pressure antinodes. At nodes or antinodes $r_{x\,cr} = f(p_{ac})$ and therefore also the primary Bjerknes forces disappear.

If two bubbles are close to each other, then the pulsation of one bubble creates pressure waves around the neighboring one. Essentially, a bubble responds to the gradient of the sound wave emitted by another bubble in the same way it behaves in relation to the primary sound field.

The force acting on the bubbles is called the secondary Bjerknes force. In a multi-bubble acoustic field, the secondary Bjerknes force is long-range [8,9,16,]. Under the influence of the secondary Bjerknes force, the bubbles come closer and merge, forming large bubbles, which then float up and leave the liquid. Thus, in acoustic degassing processes, the growth of bubbles due to their fusion is an important factor that is controlled by the secondary Bjerknes force.

For two pulsating bubbles, the Bjerknes force is described by the formula

$$F_B = \rho_l \frac{4\pi R_1^2 R_2^2\cdot(dR_1/d\tau)\cdot(dR_2/d\tau)\cdot\cos\phi}{r_x^2}, \qquad (2)$$

Where $r_x(\tau)$ is the distance between the centers of the bubbles. If the pulsations occur in one phase ($\phi = 0$), the bubbles must approach each other with increasing speed until their surfaces touch, otherwise they will diverge. The following assumptions are used.

1). During the pulsation process, the bubbles retain their spherical shape.

2) At a given frequency of US oscillations, the wavelength is much greater than the distance between the centers of the bubbles $\lambda = c_{ac}/f_{ac} >> r_x$.

Recently, a large number of experimental studies of the interaction of a pair of bubbles in an US field under the influence of the Bjerknes force have appeared in a wide range of bubble sizes, frequencies and acoustic pressures. A detailed review of these works is contained in publications [15, 21, 22]. The main results of these studies should be noted as follows.

Two bubbles with $R \approx 22$ μm, located at a distance of r_{x0}=1.3 mm in an UW field with f_{ac} = 24.6 kHz and p_{ac} = 40 kPa, approach each other with an initial speed of 0.02 m/s and by the time of merger their speed reaches 0.12 m/s . [23].

A pair of bubbles with $R \approx$=30 μm, located at a distance of r_{x0} = 180 μm in an US field with f_{ac} = 87 kHz and a power of 5 W, approach and coagulate after 70 μs with an average speed of 2.6 m/s. As they approach, the radii of the pulsating bubbles are ranging from $R_{\max} \approx 50$ μm to $R_{\min} \approx 9$ μm, and the approach speed at the final stage are varying from –5 m/s to 20 m/s. [9]

In [22], the interaction of two bubbles with different radii ($R_{10} > R_{20}$) pulsating in an US field with f_{ac}=20 kHz and p_{ac}=10 kPa was numerically studied. For bubbles with R_0 5÷25 μm, the frequency of natural oscillations in water is $f_{res} \propto 200$ kHz. Because $f_{ac} << f_{res}$ the bubbles pulsate in the same phase and approach each other according to Bjerknes' law. However, near the contact, viscous forces can compensate for the attractive force, which prevents coalescence. It has been shown that bubbles merge under the condition $R_{10}/R_{20} < 3$, otherwise periodic pulsations stabilize and fusion does not occur. These theoretical results are consistent with existing experiments [B6].

In [21], the influence of pulsations of a small bubble on the bubbles interaction in an US field is considered for large ($R_{10} \geq 20$ μm) and small ($R_{10} \geq 3$ μm) sizes of a pair of bubbles. As the radius of the larger bubble increases, the value of the Bjerknes force changes from negative to positive. There is a critical distance $r_{x\,cr} = f(p_{ac})$ that can lead to a transition between mutual attraction and repulsion of bubbles.

The effects of surfactants on bubble dynamics in acoustic degassing processes manifest themselves in several ways. As shown above, the presence of small surfactant additives increases the rate of bubble growth during rectified diffusion by creating interfacial resistance at the interface. For the same reason, the presence of surfactant additives in water prevents the coalescence of bubbles under the influence of the Bjerknes force due to the electrostatic effect caused by the adsorption of charged surfactant molecules on the surface of the bubble. This leads to a decrease in the total volume of bubbles in a multi-bubble field [9,15].

With regard to problems of acoustic degassing, the main results of these studies are that the rate of bubble growth and gas accumulation as a result of the approach and merging of bubbles under the influence of Bjerknes forces occurs much faster than in the processes of rectified diffusion.

Interaction of bubbles of different sizes under the influence of the Bjerknes force. The work [24] describes a previously unknown effect of the interaction of pulsating bubbles under the influence of the Bjerknes force, discovered during a theoretical analysis based on the model of the dynamics of a single bubble [25]. It has been established that two pulsating bubbles of the same radius approach each other in strict accordance with Bjerknes' law only if their radius R_0 is above a certain boundary value $R^* = f(f_{ac}, p_{ac})$. If $R_0 < R^*$, the bubbles diverge (Fig. 3).

The analysis showed that the parameter $R*$ lies in the subcritical region of bubble sizes ($R* < R_{cr}$) and is inversely proportional to frequency f_{ac} and acoustic pressure p_{ac}. In this regard, the question arises about the interaction in an US field of two bubbles of different sizes ($R1_0 > R2_0$), if for given values of f_{ac} and p_{ac} radius $R1_0 > R*$, whereas $R2_0 < R*$. To analyze this situation, we carried out a computational experiment on the interaction of such bubbles in an US field with fixed values of f_{ac} and p_{ac}. It is obvious that for given values of f_{ac} and p_{ac} equilibrium radii of the bubbles $R1_0$ and $R2_0$ should not exceed their critical values R_{cr}, otherwise one of the bubbles or both will disappear already in the first periods of field oscillation.

As in [24], the computational experiment was carried out on the basis of the mathematical model described in [25]. Within this model, the pressure in the liquid in the vicinity of each bubble, taking into account the influence of the neighboring pulsating bubble, is determined by the relation

$$p_l(r_x,\tau) = p_0 + \left[p_b - p_0 + \frac{1}{2\rho_l w_R^2}\left(1 - \frac{R^3}{r_x^3}\right) - \frac{2\sigma}{R} - \frac{4\mu_l w_R}{R} \right] \cdot \frac{R}{r_x}. \qquad (3)$$

Here, ρ_l, μ_l, σ are the density, viscosity and surface tension of the liquid, respectively; w_R is rate of change of the radius of the pulsating bubble; p_b is pressure of the gas medium inside the bubble; $p_l(\tau) = p_0 + p_{ac} \cdot \cos \omega\tau$ is the liquid pressure far from the bubbles.

Some results of this computational experiment are presented in Figures 4 and .5. Generalization of these results allows us to draw the following conclusion. It turned out that for all the studied modes the parameter $R* = f(f_{ac}, p_{ac})$, still remains the criterion that determines the direction of the relative movement of the bubbles. In the case of interaction between bubbles of different sizes, the averaged equilibrium radius $R_0^{cp} = (R1_0 + R2_0)/2$ should be used as the equilibrium radius R_0. Any two pulsating bubbles (the same or different in size) will approach each other until they merge completely if $R_0^{cp} > R*$. Otherwise, bubbles should be observed to diverge.

As shown in Figs. 3 and 4, with field parameters f_{ac}=10 kHz and p_{ac}=100 kPa, the boundary radius $R*$=3.98 μm. The curves shown in Fig. 4 describe the nature of the interaction of five pairs of bubbles with different values of equilibrium radii $R1_0$ and $R2_0$. Curves 1 and 2 correspond to two pairs of bubbles with an average radius of R_0^{cp}=3 μm. Since the meaning of $R_0^{cp} < R*$, the bubbles in both pairs diverges. Curves 3, 4, and 5 in this figure correspond to the interaction of three pairs of bubbles with an average radius R_0^{cp}= 4.5 μm. Since the value of $R_0^{cp} > R*$, the bubbles in all three pairs should approach each other, which is confirmed by the curves presented in the figures.

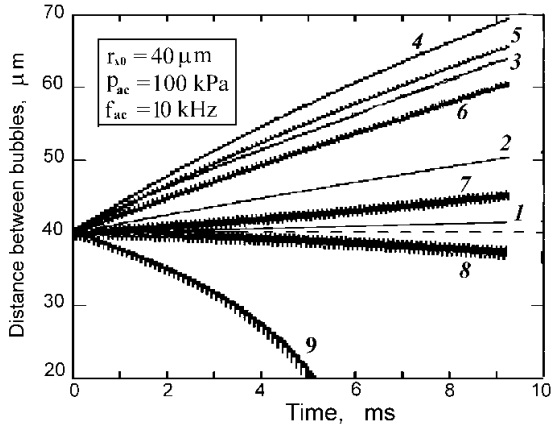

Fig. 3. Change in time of the distance between two bubbles of the same size during their pulsation in an US field at different values of their equilibrium radius R_0: **1** – 1.0 μm; **2** – 2.0 μm; **3** – 2.7 μm; **4** – 3.0 μm; **5** – 3.3 μm; **6** – 3.7 μm; **7** – 3.95 μm; **8** – 4.0 μm; **9** – 4.2 μm. With the specified conditions of the US field the boundary radius $R^* = 3.98$ μm

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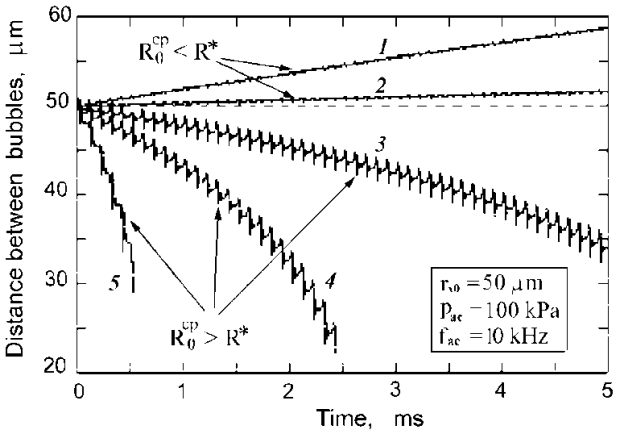

Fig.4. Change in the distance between two pulsating bubbles, with different values of their radii $R1_0$ and $R2_0$. The interaction of five pairs of bubbles with the following values $R1_0$ and $R1_0$: **1** – 4 and 2 μm (R_0^{av}= 3 μm); **2** – 5 and 1 μm (R_0^{av}=3 μm); **3** – 5 and 4 μm (R_0^{av}= 4.5 μm); **4** –6 and 3 μm (R_0^{av}=4.5 μm); **5** – 8 and 1 μm (R_0^{av}=4.5 μm); With the specified conditions of the US field the radius $R^* = 3.98$ μm

At the same value R_0^{cp}, the speed of the relative movement of the bubbles depends on the value of the ratio $R1_0/R2_0$. The lower this value, the faster the bubbles come together, as can be seen from a comparison of curves 3, 4 and 5. For diverging bubbles, on the contrary, the lower the value $R1_0/R2_0$, the slower the bubbles diverge, as evidenced by a comparison of curves 1 and 2.

The movement of bubbles relative to the liquid in each of these pairs is shown in Fig. 5. The numbering of the bubbles is the same as in the previous figure. When bubbles approach each other, small and large bubbles move towards each other, but the speed of the small bubble in each pair is significantly higher than that of the large one. In diverging bubbles, small bubbles quickly move away from large ones during pulsations, and large bubbles, on the contrary, move relative to the liquid in the direction of small bubbles. The result of this movement is the mutual divergence of the bubbles.

An analysis of the results of a computational experiment on the interaction of bubbles showed that the boundary radius R^* changes in inverse proportion to the field frequency. If in an US field with a frequency f_{ac}=10 kHz and acoustic pressure p_{ac} =100 kPa R^*=3.98 μm, then when the field frequency is reduced to f_{ac}=4 kHz the value increases to R^*=5.3 μm. A change in acoustic pressure has a stronger effect on the value R^*. In an US field with a frequency field f_{ac}=10 kHz, a decrease p_{ac} from 100 kPa to 50 kPa leads to an increase R^* from 3.98 μm to 24 μm.

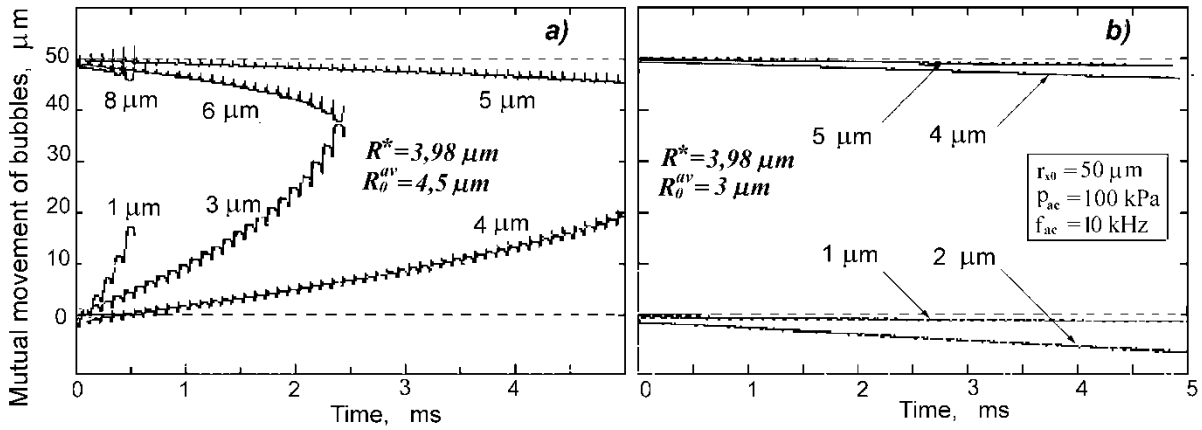

Fig. 5. Movement of the centers of two bubbles, pulsating in an acoustic field, with different values of their radii $R1_0$ and $R2_0$. The calculation was carried out under the same conditions and for the same five pairs of bubbles, which are shown in Fig.4. Pairs of bubbles with values R_0^{av}=4.5 μm> R^* (**a**) and R_0^{av}=3 μm < R^* (**b**) are shown.

The speed of convergence of micron-sized bubbles in an US field under the influence of the Bjerknes force is quite high and is measured on a m/s scale.

The existence of the effects described above forces us to take a fresh look at the mechanism for establishing the developed cavitation regime and to look for new approaches to substantiate the optimal conditions for the acoustic degassing of liquids

Analysis of research results. The analysis of the current state of modeling the study of acoustic degassing processes leads to the conclusion that despite the increase in publications on this topic every year, many aspects of ultrasonic degassing are still far from being studied. The problem is that the physical nature and mechanism of degassing at the micro level remain unclear. There are contradictions regarding these basic mechanisms of ultrasonic degassing. According to most researchers, it is necessary, first of all, to find out the reasons for the stable state of already existing nano-sized bubbles. The concentrations of dissolved and free oxygen in water were determined by NMR. Measurements have shown that 1 m3 of water at 20°C contains about $2 \cdot 10^{15}$ bubbles with an average radius of ~20 nm [25]. After 30 min of ultrasonic irradiation, the total volume of air in the bubbles decreased by almost half. At the same time, the amount of dissolved oxygen decreases by only 12%, which corresponds to a decrease in air solubility when water is heated by 4.5°C. The mechanism of this phenomenon has not been discussed, but it is obvious that irradiation leads to the release of bubbles from water without a noticeable change in air solubility.

There are contradictions regarding these basic mechanisms of ultrasonic degassing. Even if there are stable nano-bubbles in the liquid volume, in accordance with the results of [25, 26], they cannot act as rectified diffusion sinks, except for values of 2 MPa. Therefore, degassing observed at lower values cannot be explained only by rectified diffusion [13, 14, 26].

At the same time, the mutual attraction of small bubbles below the Blake threshold turns out to be very weak and therefore the fusion of such micro-bubbles under the influence of the Bjerknes force is extremely slow. According to the authors of [8], the merging time of two single bubbles with radii, located at a close distance from each other, at =0.1 MPa is about 7.5 minutes, and at = 0.5 MPa – more than 4 hours. In this regard, the question is being discussed whether the gas dissolves completely to the molecular level or whether very small “pockets” or nano-bubbles may exist in the liquid, which can act as cavitation nuclei [8,26].

Another important problem is the fact that a structured bubble cluster is formed at the surface of the ultrasonic transducer, which poorly transmits sound waves, which worsens the acoustic behavior of the liquid and leads to the formation of chaotically changing bubble structures in it [5,9,12-16].

These are just a few of many reasons that complicate the problem of adequate modeling of acoustic degassing processes

Conclusion. Acoustic cavitation is a complex and dynamic process where its spatial distribution and magnitude are very sensitive to the type of transducer used, the ultrasonic treatment mode, the geometry of the reactor, the volume of liquid, and the type and amount of dissolved gases. as well as the concentration and surface activity of the solutes in the solution.

Although the dynamics of individual bubbles and the basis of their interactions are largely well understood, understanding, modeling and predicting the behavior of systems containing multiple acavitation bubbles remains a major challenge. Real-life ultrasonication applications involve multi-bubble fields where bubble interactions become important. In particular, elucidation of the dynamics of bubble clusters, which plays a decisive role in the processes of acoustic degassing, requires further research, including theoretical and experimental work.

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Фізика аеродисперсних систем. – 2023. – № 61. – С.227-240

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Деякі проблеми моделювання кавітаційної дегазації рідини. І. Акустична кавітація.

АНОТАЦІЯ

В останні десятиліття широкого застосування набувають кавітаційні методи дегазації рідини, які сьогодні практично замінили в промисловості традиційні трудомісткі механічні та хімічні методи дегазації. Застосування кавітаційних методів базується на тому, що частина присутніх в рідині нейтральних газів знаходиться не в розчиненому стані, а у так званому «вільному» стані у складі великої кількості парогазових бульбашок, розмір яких вимірюється в масштабі мікро- та нанометрів. Природа стабільного довготривалого існування таких мікро-бульбашок, до цього часу не знайшла обґрунтованого пояснення і є предметом дискусії дослідників. Кавітаційні методи дегазації, як гідродинамічні так і акустичні, спрямовані саме на швидке видалення цих бульбашок з рідини разом з присутнім в них вільним газом. Перевагою застосування методів акустичної кавітації є можливість точного контролю частоти та інтенсивності ультразвуку, а також тривалості озвучування Методи акустичної дегазації базуються на двох механізмах: перехід розчиненого газу всередину пульсуючих бульбашок завдяки ефекту «спрямованої дифузії» та зближення і наступна коалесценція сусідніх бульбашок під дією сили Б'єркнеса. Як наслідок, зростаючі бульбашки швидко спливають і виходять з рідини разом вільним газом. В останні роки опубліковано велику кількість статей по комплексному дослідження процесів акустичної дегазації. На думку авторів цих публікацій механізм дегазації на мікроскопічному і все різноманіття динаміки бульбашок, в залежності від частоти та інтенсивності звуку, залишається поки що не зрозумілими.

В даній статті розглянуто основні проблеми моделювання процесів акустичної дегазації, які підтверджують відсутність загальноприйнятих чітких уявлень про фізичну природу і механізми кавітаційних явищ та загального підходу до аналізу отриманих результатів. В плані розвитку досліджень в цьому напрямку в статті також наводяться результати обчислювального експерименту по коалесценції пульсуючих бульбашок, проведеного авторами на основі створеної ними раніше моделі динаміки одиничної бульбашки. В результаті теоретичного дослідження одержано нову, невідому раніше інформацію про силову взаємодію пульсуючих бульбашок різного розміру, що можна розглядати як певний внесок в розуміння механізмів акустичної дегазації.

Ключові слова: *акустична дегазація, газові мікро-бульбашки, моделювання, коалесценція*