Experimental Study of the Processes of Formation, Drift and Coalescence of Vapor-Gas Bubbles in Aqueous Solutions of Salts and Surfactants in a Sonochemical Reactor

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Abstract. An experimental study of the activity of cavitation processes and the intensity of coalescence of vapor-gas bubbles arising in the volume of a liquid in the presence of ultrasonic (US) exposure in a NaCl salt solution and at various concentrations of sodium dodecyl sulfate (SDS) as a surfactant has been carried out. The process of bubble formation and drift was recorded using a high-speed camera in the plane of the cuvette illuminated by a laser knife. It is shown that the addition of a surfactant to an aqueous solution of NaCl salt leads to a partial inhibition of the coalescence of the observed bubbles and a change in the degassing mode of the liquid in the presence of ultrasonic treatment. The maximum activity of cavitation processes and the formation of vapor-gas bubbles was observed in the presence of salt and a low concentration of SDS. Thus, the presence of a surfactant in an aqueous solution of 0.1 M NaCl salt leads to a change in the growth dynamics of the bubble ensemble, since small bubbles are not able to float to the surface, due to the prevalence of viscous and vibrational forces over buoyancy force.

1. Introduction

Under the influence of ultrasound, inertial and non-inertial (inactive) cavitation bubbles can form in a liquid. The activity of bubble formation due to the processes of cavitation and coalescence depends on many factors, as a result, both the collapse of vapor-gas cavitation bubbles in the liquid and their coalescence and long-term existence of relatively large bubbles can be observed [1, 2].

Controlling the formation of inertial cavitation bubbles is an important task for optimizing the operation of sonochemical reactors. [3, 4, 5, 6, 7, 8]. The course of sonochemical reactions directly depends on the intensity of formation of hydroxide radicals, the volume of formation of which depends on various parameters, such as: liquid viscosity, liquid surface tension, amplitude and frequency of ultrasonic action, shape and dimensions of the reactor, many others [9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. The chemical synthesis of substances that occurs in liquids filling sonochemical reactors depends on the presence of impurities, since impurities can change some of the physicochemical parameters characterizing the liquid. So, in work [19], the activity of cavitation processes was observed with the help of photographs, sonoluminescence and the process of luminol luminescence. The paper describes the influence of the power of ultrasonic action and the added surfactant (SDS) on cavitation fields. It was found that the addition of SDS at a low concentration (less than 1 mM) leads to an increase in the intensity of sonoluminescence.
Salts, like surfactants, affect the process of cavitation activity [20, 21, 22, 23, 24, 25]. Thus, in [26], the activity of cavitation processes in the presence of NaCl salt was investigated. It was found that the intensity of sonoluminescence increases with salt concentration due to a decrease in gas solubility, which leads to less coalescence, less attenuation of the ultrasonic wave and the formation of a standing wave. All these effects contribute to an increase in the number of sonoluminescent bubbles, at least up to a certain concentration.

The field of science associated with the use of ultrasonic treatment in the flotation process is also actively developing [27, 28, 29, 30]. The effects arising in a liquid under the action of ultrasound can increase the selectivity of extracting valuable ore from the pulp [31, 32]. The search for the optimal technological scheme of flotation led the researchers to the idea of using ultrasound directly at the stage of de-sludging, when the ultrasound is able to purify valuable ore from clay impurities [33]. The positive effect of ultrasonic treatment during flotation may be due to the generation of microbubbles deposited on the surface of the particles. Microbubbles increase the probability of fixing large bubbles of the order of one mm on the surface of the mineral, and play the role of a secondary collector [34, 35]. In addition, ultrasonic action creates areas of low pressure in the liquid, into which particles and bubbles are drawn under the action of the primary Bjerknes force. Thus, the likelihood of their collision increases, which has a positive effect on the flotation process. Most of the works devoted to the study of the influence of ultrasonic treatment on the flotation process tell about a positive effect, although in some works, for certain parameters of ultrasonic treatment, the negative impact of ultrasound is also described [36]. The use of ultrasonic treatment for intensifying chemical reactions and optimizing the process of enrichment by the flotation method requires additional fundamental research related to the process of formation and dynamics of vapor-gas bubbles arising as a result of ultrasonic treatment of liquids. The revealed regularities in the dynamics of bubbles in the presence of surfactants and NaCl salt will expand the range of knowledge on the use of ultrasound in various applications. This work is devoted to the study of the formation of cavitation bubbles and the intensity of the process of their coalescence in a NaCl salt solution in the presence of SDS surfactant monomers.

2. Description measurement method

In the experiments, we used a parallelepiped-shaped cell with dimensions of $110 \times 116 \times 160$ mm $3$ Fig. 1. The cuvette was made of 3 mm thick plexiglass. To visualize the bubbles, a laser knife created by a cylindrical lens and a blue laser was used. A high-speed camera was used to record the dynamics of the bubbles.

![Figure 1](image_url)

**Figure 1.** Diagram of the experimental setup and measurement technique: 1 ultrasound generator, $f = 28$ kHz, $P = 60$ W; 2 - metal disk, $d = 88$ mm, 3 - laser; 4 high speed camera

In all experiments, a stainless steel metal disk 88 mm in diameter was used as the ultrasound source, placed at the bottom of the cuvette so that the center of the emitter coincided with the center of the bottom of the cell. It was connected to a generator of ultrasonic vibrations with a frequency of $f = 28$ kHz and a
maximum power of $P = 60 \text{ W}$. The photographs obtained during the experiments were used to analyze the temporal dynamics of the appearance and drift of bubbles.

To process the photographs obtained during the experiment, an algorithm was used, consisting of the following sequential actions: Binarization of the image. Thus, the image turns into an array consisting of 0 and 1. In this case, the bubbles correspond to a pixel with a value of 1, and the blank space on the surface of the plate corresponds to a pixel with a value of 0.

Then the total number of pixels with a value of 1 in the entire image was summed up, the number of which corresponded to the area of the bubbles at some point in time binarization, the moment of exposure to ultrasound.

The analysis of the time sequence of the images thus provided the construction of a curve based on 500 photographs.

Before turning on the ultrasound, background bubbles were recorded using a laser knife and a high-speed video camera in the same vertical plane as during the experiments in Fig. 2. In both cases, the area of the illuminated region created by the bubbles did after using not exceed 0.01%.

Distilled water was used as a liquid. Chemically pure NaCl (ChemCenter) was used as a salt, SDS was used as a surfactant. After the preparation of distilled water, it was settled for at least a day at normal atmospheric pressure and a temperature of $22^\circ \text{C}$.

3. Results
In the experiments, the processes of occurrence, drift and coalescence of non-inertial cavitation bubbles in distilled water and in an aqueous solution of NaCl at a concentration of 0.1 M were observed, while the concentration of SDS varied from 0.05 mM to 0.2 mM. When the resonance size was reached, the bubble collapsed, creating new nuclei, or dissolved in the liquid. In some cases, the bubbles, being in the compression phase, are able to overcome the resonance size, and thus exist for a long time [1, 2], these non-

![Figure 2. a - An example of an image after cropping, b - an example of an image](image)

![Figure 3. a - photograph obtained by combining 500 frames for pure water, b - in the presence of 0.1 M NaCl and a low concentration of SDS equal to 0.05 mM](image)
inertial vapor-gas bubbles were mainly recorded by the camera. In Fig. 3 shows images obtained by combining 500 frames for pure water and in the presence of 0.1 M NaCl and a low SDS concentration of 0.05 mM.

Let us consider in more detail the mechanism of coalescence in water: the surfaces of bubbles do not contain additional layers of molecules that prevent coalescence, therefore even small bubbles, actively merging, form rather large freely drifting vapor-gas bubbles. The area of illumination in this case increases, however, upon reaching millimeter sizes, the bubbles float under the action of the Archimedes force on the liquid-gas interface, which causes degassing of the liquid in the cuvette [37]. Figure 4 shows the time dependence of the illuminated surface area for pure water. The dependence is close to linear, which is explained by the activity of the formation of cavitation bubbles with their subsequent coalescence.

Figure 5 shows the time dependence of the illumination area and a schematic representation of the electric double layer. At the initial moment of time, a sharp decrease in the area of illumination is observed, which is associated with the separation of bubbles from the walls of the cuvette due to ultrasonic action. From the 200th frame, a decrease in the illumination area is observed according to a law close to linear, which is associated with the process of degassing of the liquid as a result of the coalescence of bubbles and their ascent. In this case, the presence of salt at a concentration of 0.1 M does not affect the probability of coalescence and is 100 percent, as for water [21]. It is possible that this fact explains that by the 600 frame the area of the illuminated region in pure water and in the presence of 0.1 M NaCl is 0.15 percent of the total area [38].

In Fig. 6 shows the time dependence of the area of the illuminated region in the presence of 0.1 M NaCl for various SDS concentrations. It was found in experiments that the surfactant leads to the process of inhibition of coalescence. Being adsorbed at the bubble-liquid interface, the surfactant leads to a local change in the physicochemical properties of the medium, such as viscosity, zeta potential, and surface tension. Inhibition can also be explained by the fact that the presence of surfactant monomers in the sorption layer of bubbles leads to screening of electrostatic fields and a decrease in the Debye length, thus repulsive forces prevail over attractive forces. For an SDS concentration of 1 mM, at the initial moment of time, an area light is observed equal to 3 percent of the total area of the illuminated surface.
Figure 5. a - Time dependence of the area of the illuminated region in the presence of 0.1 M NaCl b - schematic representation of the adsorption and diffusion layer near the gas-water interface

Such a large size of the area is explained by the fact that at a high concentration of surfactants on the surface of the liquid foam was formed. When the ultrasound was turned on, the foam from the surface was pumped into the volume of the liquid, approximately into the nodes of the formed standing acoustic wave. From the graph it can be concluded that the minimum surfactant concentration of 0.05 mM provided the maximum cavitation activity and the maximum number of gas bubbles was observed in the experiments [19]. Based on the data obtained, it can be concluded that a decrease in the SDS concentration from 1 mM to 0.05 mM leads to an increase in the activity of cavitation processes and the number of formed bubbles. In contrast to water, after 100 frames and throughout the entire experiment, the area of the illuminated surface does not change and is about 2 percent, due to a decrease in the rate of the degassing process, since a long-term ultrasound exposure ultimately degasses the liquid.

4. Conclusions
An experimental study of the activity of cavitation processes and the intensity of coalescence of vapor-gas bubbles arising in the volume of a liquid in the presence of ultrasonic (US) exposure in a NaCl salt solution and at various surfactant concentrations sodium dodecyl sulfate (SDS) showed that the formation and drift of bubbles depends on the presence of salts and surfactants in water. It was found that in water bubbles quickly reach a critical size and immediately float to the surface, and the addition of a surfactant to an aqueous solution of NaCl salt leads to partial inhibition of the coalescence process of bubbles of millimeter diameter, thereby slowing down the degassing process (indirect observation). The maximum activity of cavitation processes and the formation of vapor-gas bubbles was observed in the presence of salt and a low...
concentration of SDS equal to 0.05 mM. Thus, the presence of a surfactant in an aqueous solution of 0.1 M NaCl salt leads to a change in the growth dynamics of the bubble ensemble due to a change in the activity of cavitation processes.

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