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Dynamics of Vapor-Gas Bubbles in a Liquid Near Solid Surfaces with Different Properties

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Abstract. In this paper, the dynamics of vapor-gas bubbles arising in a distilled water and water-salt solutions as a result of coalescence of cavitation bubbles formed under the action of ultrasound (US) near solid surfaces with different properties has been experimentally investigated. Experiments have shown a significant effect of salt concentration in water and properties of solid surface on the behavior of bubbles, both under the action of ultrasonic and after its shutdown. In distilled water, mobile bubbles were observed on hydrophilic surface of wood, most of which are detached from the surface and rise after US shutdown. Bubbles on the hydrophobic surface of fluoroplastic, on the contrary, remain motionless both during the exposure to ultrasonic and after its shutdown. In a 20% aqueous solution of NaCl under the action of ultrasound on the hydrophilic surface, the bubbles remain stationary, and at the time of the shutdown of the ultrasound only a small part of them rise. In similar conditions, mobile bubbles are observed on the hydrophobic surface that rise when the ultrasonic is switched off.

1. Introduction

Under the influence of ultrasound cavitation bubbles are formed in water. Their further behavior depends on various factors, there can be observed both the collapse of cavitation bubbles in a liquid, and their coalescence and long existence of relatively large bubbles [1,2]. The interaction of cavitation bubbles with solid surfaces is also a subject of discussion [3], in particular, due to the formation of nanobubbles under the action of ultrasonic, which can change the surface properties of a solid surface, for example, increasing the likelihood of large bubbles attaching to a solid surface when they touch [4]. Interest in such studies, in particular, is due to the fact that under the action of ultrasound erosion of solid surfaces occurs, and its intensity in salt solutions is higher than in pure water [5].

The problem of the interaction of bubbles with ore particles in the process of their enrichment by the flotation method deserves special attention. According to the available theoretical and experimental data, it can be concluded that the effect of ultrasound on the flotation pulp can increase the efficiency of flotation [6]. This behavior may be associated with the following effects: additional generation of a larger number of cavitation microbubbles in the pulp during its irradiation with ultrasonic, an increase in the trajectory of ascent of bubbles, the action of averaged forces arising in vibration fields [7], generation of vapor-gas nanobubbles formed in microcracks of solids [8-10], the change in the value of the Zeta potential on the surface of the bubble [11,12]. Some authors also point out the negative impact of ultrasonic exposure, in particular on the flotation process, since at a certain critical value of sound pressure there is a decrease in the percentage of valuable ore recovery [13].

One of the reasons for the positive or negative effect of ultrasound on the flotation process is that it affects the interaction of bubbles with solid surfaces due to the appearance of additional acoustic forces [14,15]. In [16], the interaction of two bubbles caused by the action of the Bjerknes force is discussed in the case when two bubbles in an acoustic field are attracted to each other. As a result of convergence,



under certain parameters, their coalescence occurs. Also, ultrasonic impact can contribute to the retention of a bubble on a solid surface due to the formation of gas nanobubbles in microcracks of a solid surface. In [17], it was experimentally observed how nanobubbles covered the microcracks of solids, and in [18], the change in the structure of a solid surface under the action of ultrasound was shown. All these effects can influence the dynamics of vapor-gas bubbles near the solid surface.

In this paper, we experimentally investigate the effects observed when bubbles approach each other with a solid surface, followed by their fixation and retention. In addition, the features of coalescence of vapor-gas bubbles in water and water-salt solutions of different concentrations arising on the surface of solids with different surface properties under the action of ultrasonic are discussed.

2. Experimental technique

The experiments were carried out in a parallelepiped-shaped cuvette with dimensions of $110 \times 116 \times 160$ mm³ (Fig. 1). The cuvette was made of 3 mm thick plexiglas. In the central part of the cuvette, the samples under investigation were fixed at an angle of 45 to the horizon; a laser knife created by a cylindrical lens and a KLM-532 laser using a DPSS green laser was used to visualize the bubbles. A high-speed camera was used to record the bubble dynamics. Degassed distilled water and aqueous solutions of chemically pure NaCl, in various mass concentrations, were used as the studied liquids.

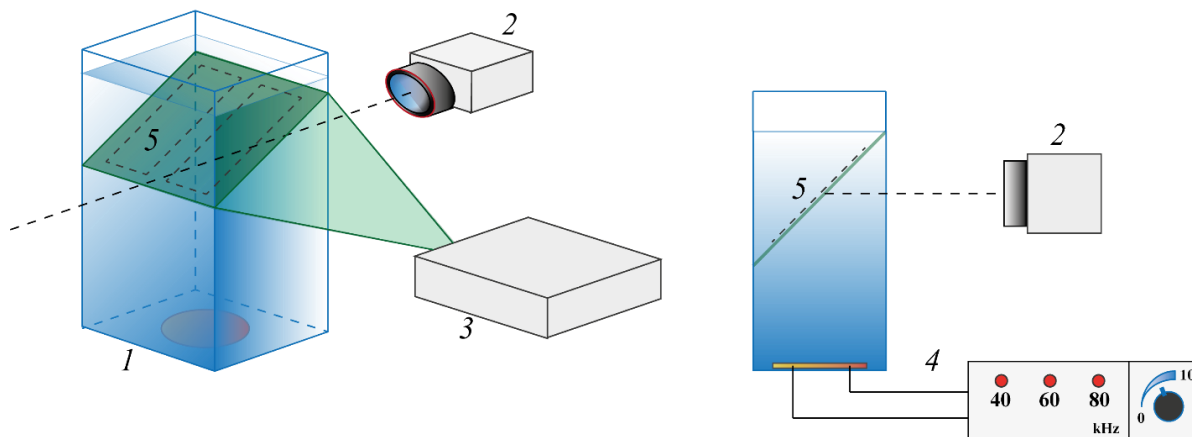


Figure 1. Laboratory setup: 1) cavity $110 \times 116 \times 160$ mm³; 2) high speed camera or reflex camera, 3) laser, 532nm; 4) ultrasound source $f=40$ kHz, $P=100$ w; 5) wood or fluoroplastic plates

A metal disk with a diameter of 88 mm, placed at the bottom of the cell, was used as the source of ultrasound so that the center of the radiator coincided with the center of the bottom of the cell. It was connected to an ultrasonic oscillator with a frequency of $f = 40$ kHz and a maximum power of $P = 100$ w.

From the photographs obtained in the course of the experiments, the critical diameter of the bubbles retained on solid surfaces was tracked. The dynamics of bubbles near solid surfaces with different surface properties were also investigated: the surface of wood with a high degree of wettability by water and the surface of a fluoroplastic with much more pronounced hydrophobic properties.

3. Results of the experiments

Distilled water

As shown by experiments conducted with distilled water and solid plates of wood and fluoroplast, under the action of ultrasound in a liquid cavitation bubbles are formed, the diameter of which increases with time due to coalescence, in the future some of the bubbles formed can be fixed on a solid surface. Depending on the surface properties and the composition of the liquid, the bubbles either adhere to the surface or drift along it.

Fig. 2a, b present photographs obtained in experiments with plates made of wood and fluoroplastic in distilled water. The photos clearly demonstrate the difference in fixing vapor-gas bubbles on surfaces with different wettability properties. Figure 2c shows the diasteter distribution of bubbles attached to the surface, 2 minutes after the start of the ultrasonic effect.

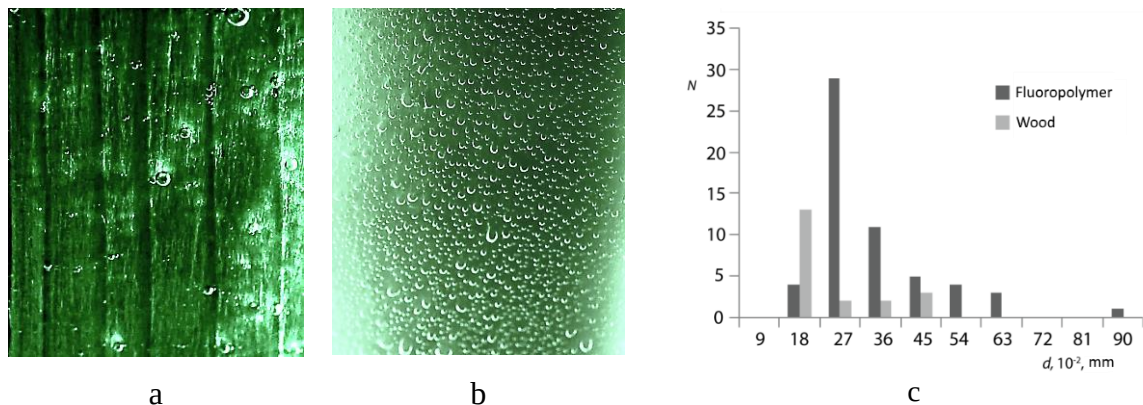


Figure 2. Photo of surface a - wood, b - fluoroplastic in distilled water under the action of ultrasonic; c is the distribution of the diameter of the bubbles attached to the surface, depending on its properties, where N is the number of bubbles

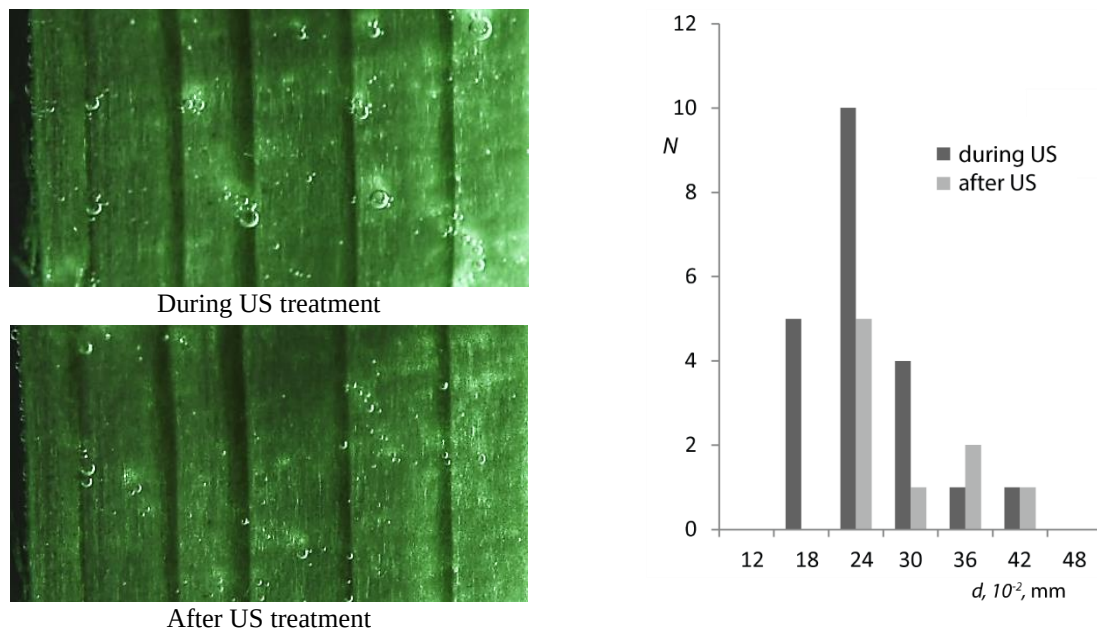


Figure 3. Size distribution of bubbles attached to the wood surface at the time of the impact of ultrasound and 5 seconds after it is switched off

On the hydrophilic surface of wood, bubbles drift, passing for 1 second a distance of about 5 to 10 of its diameter, quickly increasing in size due to coalescence and float up. In the case of the hydrophobic surface of the fluoroplast, stable attachment of bubbles is observed. Thus, the force of interaction of a bubble with a solid surface in distilled water depends on the surface properties of the solid surface, as a result of which the total number of bubbles on the wood surface is much less than on the surface of the fluoroplastic. Such features in the dynamics of bubbles can be due to the balance of electrostatic and hydrodynamic forces, namely the Archimedes force, the surface tension force, the pressure gradient arising from the averaged flows caused by the action of ultrasonic, and the secondary Bjorkens force. One of the reasons for the mobility of bubbles on wood is the predominance of hydrodynamic forces over the surface ones; in the case of fluoroplast, the main contribution is made by forces of an electrostatic nature.

Fig.3 on the left shows a photograph of the wood surface 5 seconds after the shutdown of the ultrasound, the right shows the size distribution of bubbles attached to the surface during the ultrasound impact and 5 seconds after it was turned off. As you can see, after turning off the ultrasound bubbles attached to the surface of the wood float. In the case of a fluoroplastic plate, the bubbles attached to the

surface, unlike the bubbles attached to the surface of the wood, almost do not float, but their subsequent growth stops.

The different behavior of the bubbles when turning off the ultrasound in the case of solid surfaces of wood and fluoroplastic, in our opinion, is explained as follows. The averaged vibration forces of attraction between a solid surface and a bubble, acting under the influence of ultrasound [19], cease to exist when the ultrasound is turned off. In the case of wood, these forces exceed the surface ones, so the bubbles tend to float. In the case of fluoroplastic, the surface forces exceed the hydrodynamic forces, while the bubbles remain frozen into the surface.

Water salt solutions

The size distributions of bubbles attached to the surfaces of wood and fluoroplastic when subjected to ultrasound, depending on the salt concentration are shown in Fig.4. Histograms show that for both wood and fluoroplastic, an increase in salt concentration leads to a decrease in the size variation of bubbles. Thus, as the salt concentration increases, the diameter of the bubbles decreases simultaneously and their size distribution becomes narrower.

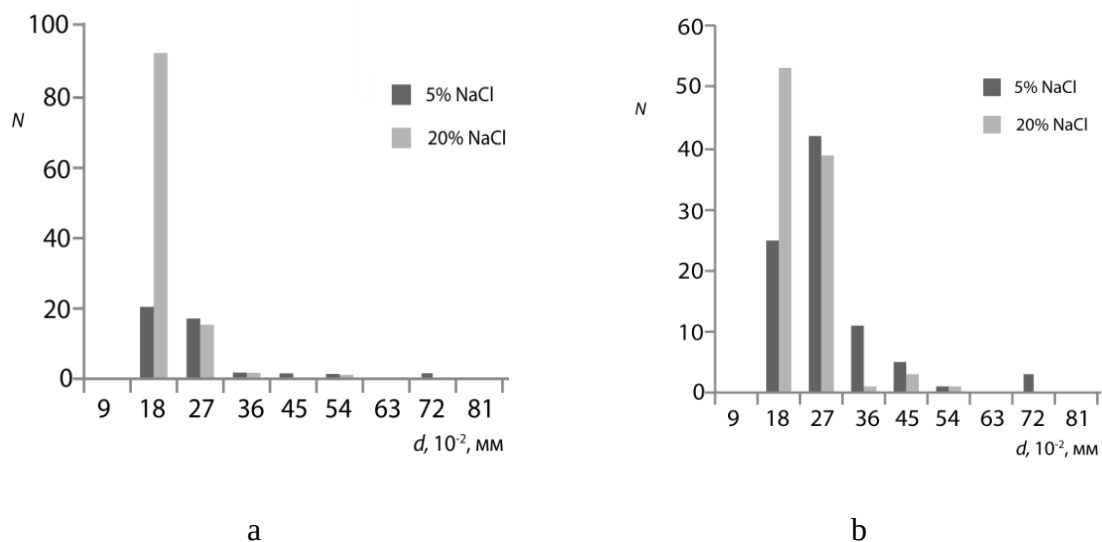


Figure 4. Comparison of histograms of the distribution of the number of bubbles from their diameter for wood (a) and fluoroplastic (b) with increasing salt concentration in water from 5% to 20%

The pattern of bubble drift also changes dramatically with changes in salt concentration. In contrast to the case of distilled water (zero salt concentration), at a salt concentration of 20%, the bubbles are frozen into the surface of the wood, but drift along the surface of the fluoroplastic. When drifting over the surface of the fluoroplastic, they additionally coalesce with the bubbles already attached to the surface, in which case their ascent occurs more intensively. As a result, by the time of the shutdown of UZ, there are practically no adherent bubbles on the fluoroplastic, while only a small amount of bubbles detach from the surface of the wood. This behavior is due to the fact that in such a system the bubbles are energetically advantageous to remain on the surface of the wood, which makes it impossible for them to coalesce. The change in the number of bubbles attached to a solid surface with time under the action of ultrasound is shown in Fig.5a for wood surface in 25% NaCl solution and in Fig.5b for fluoroplastic surface in distilled water.

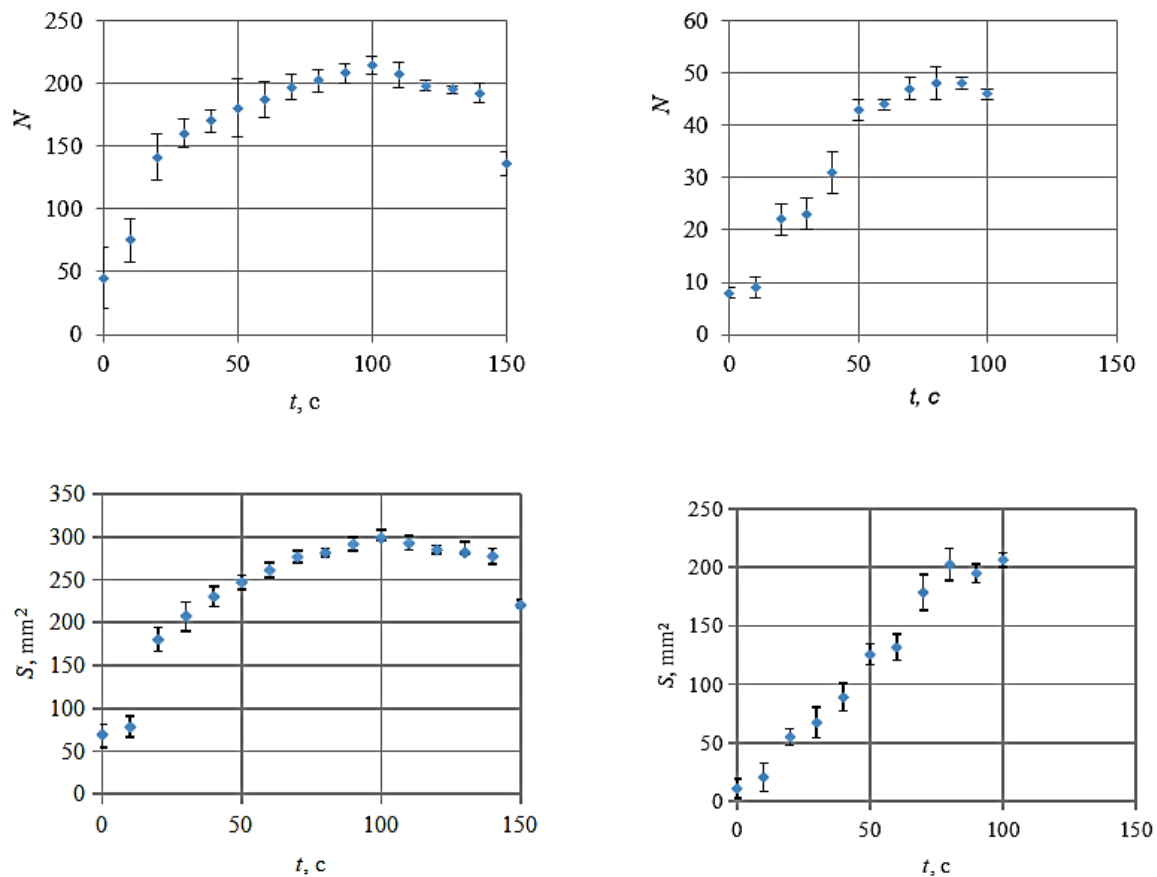


Figure 5 Changes in the number of attached bubbles and the total area of attachment of bubbles over time when exposed to ultrasound: left - to the surface of the fluoroplast, in distilled water, right - to the surface of wood in a 20% solution of salt NaCl

Fig.5 shows the time dependence of the number of bubbles and the total surface area occupied by the bubbles in distilled water and a 20% aqueous solution of NaCl salt. It is important to note that the dynamics of vapor-gas bubbles near the surface with hydrophobic properties in distilled water is qualitatively similar to the dynamics of vapor-gas bubbles near the hydrophilic surface in a 20% aqueous solution of NaCl. In both cases, the number of bubbles increases over time, however, there is a point at which the total number of bubbles near the surface does not change. The same can be said about the surface area covered by bubbles, it grows only to a certain critical value, after which the system enters the stationary mode. In distilled water, the ultrasonic effect made it possible to additionally hold 35% of the total number of bubbles on the hydrophobic surface.

4. Conclusions

As experiments have shown, in distilled water, under the action of ultrasound, moving bubbles appeared on the hydrophilic surface, most of which broke off from the surface and surfaced when the ultrasonic was switched off. However, the bubbles on the hydrophobic surface remained frozen at all stages of the experiment.

It was found that with an increase in salt concentration in water, in the case of a hydrophilic surface, the total surface area covered with bubbles first grows according to a law close to linear, and then enters the saturation stage, and the number of bubbles on both surfaces changes in the same way over time.

With a high concentration of NaCl under the influence of ultrasound on a hydrophilic surface, the bubbles remained stationary, in contrast to the hydrophobic surface, where there are moving bubbles that pop up when the ultrasonic is turned off.

Acknowledgments

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