Experimental study of formation and dynamics of cavitation bubbles and acoustic flows in NaCl, KCl water solutions

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Abstract. The acoustic flows and the phenomena associated with them arising under the action of ultrasound of different power on distilled water and aqueous solutions of a mixture of NaCl and KCl salts of various concentrations are studied experimentally. It is found that in the distilled water, under the action of ultrasound, the appearance of inertial and non-inertial cavitation bubbles takes place, then the formation of stable clusters, the distance between which depends on the power of the ultrasound source is observed. Experiments show that an increase in the mass concentration of salts in water leads to the decrease in the average diameter of the arising inertial cavitation bubbles and to the gradual decrease in their number, up to an almost complete disappearance at nearly 13% of the concentration of the salt mixture in the water.

1. Introduction
Solution of the problems associated with the practical application of ultrasound is impossible without knowledge of the acoustic field characteristics, i.e. the spatial distribution of sound pressure or the intensity of the sound wave for the case under consideration, and also without the analysis of the cavitation processes occurring in liquids under the action of ultrasound. The use of ultrasonic sources is associated with certain problems. One of them is the complexity of creating a uniform acoustic field, since even the flat radiator used in the setup [1] gives strongly non-uniform field. Since the source itself can have physical irregularities on the surface, the field observed when it is switched on looks extremely inhomogeneous, which significantly complicates the experimental investigation and interpretation of the results obtained.

Separate attention should be paid to the effect of ultrasonic radiation on solid inclusions in the liquid [2], since the distribution of cavitation bubbles on a solid sample is still insufficiently studied. It is known, for example, that the influence of ultrasound on liquid-solid systems is largely related to the chemical effects of ultrasound, which are mainly associated with the collapse of cavitation bubbles [3]. Each collapse of the bubble potentially leads to a local increase in pressure up to 500 atm and a temperature of about 5000 K, and also causes shock waves, microcurrents and surface erosion of solid inclusions [4]. These and other effects, occurring when ultrasound is applied to liquid media, attracted attention of specialists in the field of ore enrichment. As a result of the studies, some positive effects of ultrasonic on ore flotation were revealed [5].
The possibilities of increasing the efficiency of flotation, using ultrasound, on one hand, and use as a mother liquor of seawater on the other hand, are of interest at present due to the acute shortage of fresh water in certain regions [6-9]. When using solutions of KCl and NaCl salts as test liquids, one can expect a significant change in both the behavior of the whole system under study, [10,11] and the formation of air bubbles during flotation [12].

This work is devoted to an experimental study of the formation and dynamics of cavitation bubbles produced by an ultrasonic radiator in saturated solutions of KCl and NaCl. Works in this direction are not known to the authors of this article. The study is motivated by the importance of studying the effect of ultrasound on the process of flotation of potassium chloride in saturated brines of a mixture of potassium and sodium salts.

2. Experimental setup and experimental procedure
The experiment was carried out in a cell 110 * 116 * 160 mm$^3$ in the form of a parallelepiped (Fig. 1). The cell was made of plexiglass 3 mm thick. The central part of the cell was penetrated from the side by a laser sheet created by a cylindrical lens and a green DPSS laser KLM-532. To record acoustic currents, a high-speed camera was used. The shooting speed varied from 10 to 100 frames per second. As test liquids, saturated solutions of a mixture of chemically pure KCl and NaCl salts were used, in a weight ratio of 6/4. For comparison, experiments were performed with degassed distilled water.

As a source of ultrasound, a metal disk with a diameter of 88 mm was used, placed so that the center of the radiator coincided with the center of the bottom of the cell. He connected to an ultrasonic oscillator with a frequency of 40 kHz and a maximum power of 100 watts. It was possible to vary the power (60%, 80% and 100% of the maximum).

![Figure 1. Experimental setup: 1) high-speed camera, 2) laser, 3) ultrasound source, 4) plexiglass cuvette](image)
It is known [12] that the ultrasonic field of a plane acoustic radiator is concentrated in a cylindrical volume of diameter $D$ and height $Z_0$ (Fig. 2). Starting from the distance $Z_0 = D / (\Delta \lambda)$, the field widens conically. The interval from the emitter to $Z_0$ is called the near zone or the Fresnel zone. The region where $Z > Z_0$ is called the far zone, or the Fraunhofer zone. In this zone, the pressure amplitude decreases proportionally to the distance from the radiator.

For experiments with degassed distilled water at a frequency of 40 kHz, the speed of sound propagation is $c = 1500 \, m / s$, wavelength $\lambda = 37.5 \, mm$. The width of the Fresnel zone under these conditions is $Z_0 = 2.34 \, cm$, the Fraunhofer zone begins at a distance of about 2 cm from the source, after which the ultrasonic field begins to expand conically. The sine of the angle $\alpha$ between the direction of propagation of the ultrasonic wave and the beam generator is related to the geometric parameters of the setup by the formula $\sin \alpha = A^4 / D$ where, for a circular plate $A = 1.22$, the calculations in this case are given $\sin \alpha = 0.18$, whence $\alpha = 10^\circ$.

For experiments with saturated NaCl and KCl salt solutions at a frequency of 40 kHz, the acoustic wave velocity is $c \approx 1.87 * 10^3 \, m / s$, the wavelength $\lambda = 46.7 \, mm$, and the Fresnel zone is limited by the distance from the surface of the ultrasonic radiator $Z_0 = 1.46 \, cm$. The angle of deflection of the propagation of an ultrasonic wave from the beam generatrix in salt solutions is $\alpha = 15^\circ$.

In the near zone, for $Z < Z_0$, the intensity of ultrasonic oscillations can have several maxima. In the far zone, for $Z > Z_0$, the wave intensity has one maximum and decreases with distance from the beam axis.

The cavitation bubbles that arise in the liquid also affect the propagation of an acoustic wave [13].

![Figure 2. Idealized field of a plane acoustic radiator](image)

As measurements have shown, the temperature of the liquid changes under the influence of ultrasonic vibrations (see Fig. 3, which shows the experimental temperature change curve obtained with a copper-constantan thermocouple). This leads to the fact that the process of bubble induction and the type of acoustic flow vary with time.

Quite sharp temperature fluctuations against the background of its growth under the action of the general heating of the liquid, observed in the experiment after switching on the ultrasonic radiator, are related, apparently, to the collapse of cavitation bubbles that occurs near the junction of the thermocouple [3].
Figure 3. Change in the temperature of degassed distilled water under the action of ultrasound at a frequency of 40 KHz at 100% of the emitter power, at a point 5 cm from the bottom

3. Results of experiments

3.1. Experiments with distilled water

Experiments with distilled water, as in [14-15], revealed the presence of two types of ultrasonic cavitation. The first of these is inertial cavitation, which is characterized by rapid growth of the bubble in the negative pressure phase. At the onset of the half-cycle of compression, the inertial bubbles collapse sharply, and local heating and hydrodynamic perturbations in the form of microscopic waves, cumulative jets and microflows of liquid can occur. From inertial bubbles, comet-shaped streamers are formed (see Fig. 4a).
The second type of ultrasonic cavitation is a non-inertial (or stationary) cavitation, in which bubbles grow due to rectification diffusion or are compressed to a resonance size as a result of gas dissolution, and then oscillate for a long time (Figure 4b).

Figure 4b shows that non-inertial bubbles have a much larger size than inertial bubbles. However, the difference is not only in size. The lifetime of inertial bubbles is less than one tenth of a second, i.e. of the order of several periods of oscillation of the acoustic wave (this time was determined with the help of a high-speed camera, with a sampling rate of 100 frames per second). For non-inertial bubbles, the lifetime is much longer than the period of oscillation of the acoustic wave. According to the results of observations, for ultrasound frequency of 40 kHz, the lifetime of non-inertial bubbles, in some experiments, was more than three minutes. Being in the zone of low pressure, the bubble performs translational oscillations with an unchanged amplitude in one plane. For fixed parameters, non-inertial bubbles arise at the same points in space, called the antinodes of a standing wave. Then, translational oscillations of the bubble and deformation of its surface occur, while the bubble is able to capture another non-inertial bubble popping up next to it (Fig. 5a-d). Such absorption can occur many times, until the diameter of the bubble becomes critical, and the Archimedes force does not exceed the value of the Bjerkness force [16-17], due to the pressure gradient that "draws" the bubble into the antinode of the standing wave and, thereby, holds it in some area of space.

Gas bubbles in a liquid are moved from the equilibrium state by changing the external pressure and perform periodic radial oscillations. Two bubble pulsating in phase are attracted to each other by the Bjerknes force, but near the contact, attraction is counteracted by repulsion, which arises due to nonlinear interaction of the Bjerknes force and the viscous force. For oscillations of a single bubble as a result of nonlinear interaction of the radial and deformational modes at their resonance, the energy of the radial oscillations transfers to the energy of deformational oscillations with a large amplitude increase. These effects provide a qualitative explanation of experiments on the coalescence and fragmentation of pulsating bubbles in a liquid.
Figure 5. Dynamics and fusion of two non-inertial bubbles and the beginning of the emergence of a bubble of critical diameter. The length of the risks is 1 cm

In the experiments, vertical cluster formation from inertial bubbles was also observed; moreover, the distance between adjacent bubbles in the cluster, at a given power, remained unchanged in the future; the system entered the stationary mode. In Fig. 6 a-c, three photographs are shown resulting from addition of 50 frames with a shooting frequency of 100 frames per second for different powers of the ultrasonic radiator at a fixed frequency of US 40 kHz for a) 60% b) 80% c) 100% of the maximum power. The areas of dark spots are the areas of drift of inertial cavitation bubbles drawn into the antinodes of a standing wave. With increasing emitter power P, the distance between cavitation bubbles l in a vertical cluster increases linearly (Fig. 7).
3.2. Experiments with aqueous solutions of NaCl and KCl salts
Experiments with saturated solutions of NaCl and KCl salts showed that in this case, at any given power of ultrasound, only inertial cavitation bubbles arise. In Fig. 8 shows the result of combining 300 frames made at a rate of 10 frames per second for a saturated solution of NaCl and KCl salts in a ratio of 4: 6, respectively. As noted above, the wavelength in a saturated salt solution at an ultrasound frequency of 40 KHz is $\lambda = 46.7 \text{ mm}$. The distance between the singular points that are local sources of bubble
streamers located above the ultrasonic radiation source in the experiment was $\lambda / 2$ and did not depend on the power of the ultrasonic radiation.

![Image](image_url)

**Figure 8.** The emergence of inertial cavitation bubbles in a saturated solution of NaCl and KCl salts. a) power US 60%, frequency 40 KHz, b) power US 100%, frequency 40 KHz

From the photographs obtained during the experiments it can be concluded that as the intensity of the streamers' appearance increases, the type of flow that appears in the cell changes, apparently streamers that break the uniformity of the antinodes, thereby knocking out the levitating bubble from the stable zone to the high-pressure zone, after which the bubble begins to float.

A series of experiments was also conducted to study the formation and dynamics of cavitation bubbles in solutions with different concentrations of NaCl and KCl. These experiments have shown that at low salt concentrations (below 2%), there are simultaneously two types of cavitation, with the threshold of inertial cavitation higher than in distilled water. Below this threshold, during the whole series of experiments, comet-shaped streamers do not appear. With the increase in the concentration from 2% to 13%, the frequency of the appearance of streamers increases, and the average diameter of the levitating bubbles decreases. At a salt concentration of 13% virtually all levitating bubbles disappear.

In [7], devoted to the flotation in sea water, the size of the air bubbles injected by the impeller in various salts including the solutions of NaCl and KCl was measured. It was found that the bubble diameter decreases with the increase of salt concentration and the dependence of the bubble diameter on the concentration is qualitatively similar for different salts. The origin of the bubbles in [7] is different from our case: in [7] this is the injection of the air into the aqueous solution of salt under pressure, and in our case cavitation bubbles arise under the action of ultrasound, however in both cases the growth of the salt concentration leads to the decrease in the bubble size, which can have a beneficial effect on the flotation process.

Figure 9 shows the dependences of the normalized bubble diameter $D = d / d_0$ (curve 1) and of the normalized number of bubbles $U = N / N_0$ (curve 2) obtained in the experiments, on the mass concentration of the salt in the solution, $n, \%$, where $d$ is the bubble diameter in the salt solution, $d_0$ is the diameter of the freely levitating non-inertial cavitation bubble in the distilled water, $N$ is the number of levitating bubbles in the salt solution, and $N_0$ is the number of non-inertial bubbles of the diameter greater than $d = 1 \text{ mm}$ in distilled water.

Calculation of the relative diameter and number of cavitation bubbles was made on the basis of processing of photographs obtained by irradiating the cuvette with a vertical laser sheet Fig. 1.
photos obtained in this way were downloaded into the software package Wolfram Mathematica where by means of the built-in functions their sequential processing was carried out.

![Figure 9](image)

**Figure 9.** Dependences of the normalized diameter of the bubble (upper curve) and of the normalized number of inertial bubbles (lower curve) on the salt concentration

4. Conclusions
The appearance and dynamics of cavitation bubbles in water and salt solutions have been studied. It was found that a significant change in the physicochemical properties of water upon its saturation with salts of NaCl and KCl leads to a qualitative change in the regime of induction of cavitation bubbles. In distilled water, both inertial and non-inertial cavitation bubbles are observed, and in saturated salt solutions only non-inertial cavitation bubbles whose zones of occurrence are strictly fixed, and their location does not depend on the power of the ultrasonic source.

There is also the appearance of clusters consisting of cavitation bubbles located in the antinodes of a standing wave in which, under certain conditions, stable levitating vesicles arise.

The dependence of the distance between drift regions in a vertical cluster of non-inertial bubbles in distilled water on the emitter power at a fixed emitter frequency of 40 kHz is determined.

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