Experimental Study of the Acoustic Pressure Distribution in a Sonochemical Reactor

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Abstract. The work is devoted to an experimental study of the main parameters of the acoustic flow that occurs in a liquid under the influence of an ultrasound source (US) with a frequency of 1.7 MHz. To study the type of emerging currents, the method of tracer and fluorescence imaging was used; the distribution of relative acoustic pressure was found using a vibration sensor; to measure the intensity of cavitation events, thermocouple measurements were used. Experiments have shown that an increase in the concentration of the NaCl salt in the water solution reduces the intensity of vibrations when the sensor is removed from the ultrasonic source. The maximum intensity of cavitation events also changes its position, moving to the area near the ultrasonic source. Thus, the effect of an increase in the salt concentration on the type of flow in a sonochemical reactor was noted, which was also experimentally recorded in the work using light-reflecting particles.

1. Introduction

Ultrasonic processing is increasingly being used in a number of manufacturing processes. Low frequency in the range of 20 to 100 kHz is used for example for cleaning and degreasing metal objects, and ultrasonic sources with a frequency in the MHz range have found their application in megasonic cleaning \cite{1}, for example for removing small particles (micron / submicron sizes) from various surfaces, including delicate ones, such as semiconductor wafers and liquid crystal displays.

The distribution of acoustic pressure and the activity of cavitation events in sonochemical reactors is affected by both the dynamics of individual cavitation bubbles formed as a result of coalescence under the action of ultrasound \cite{2, 3}, and the high concentration of dispersed bubbles that convert the ultrasound energy into vibrations of the bubble surface \cite{4}.

Another feature of the currents that occur under the influence of ultrasound is associated with the presence of a gradient of acoustic intensity as a result of which the bubbles, under the influence of the force of acoustic radiation, can move, dragging the surrounding liquid with them \cite{5, 6}. Such a flow usually occurs in sonochemical reactors in the presence of a large number of vapor-gas bubbles. Thus, the study of flows in sonochemical reactors, despite a number of technical features, is of interest to researchers.

At this stage, researchers are mainly developing three methods for assessing the degree of activity of cavitation events:

- method based on the use of foil \cite{7} Fig. 1, (b);
- method based on the use of thermocouples \cite{8, 9} Fig. 1, (a);
- method based on piezoceramic sensors \cite{7}.
The works [1, 10] are devoted to the development of methods for determining the degree of acoustic cavitation in real time, which would quantify the degree of acoustic cavitation during a particular process. Although a number of methods were evaluated as a potential measurement tool, none of them were considered suitable for standardization [11]. However, in the article in [8], a thermostonde containing a thermocouple embedded in an acoustic absorber was used, thus numerical values of the intensity of acoustic cavitation in the region above the ultrasonic source were obtained. A similar device was also used by a number of other authors [12], [9].

The purpose of this work is to study the distribution of acoustic pressure, the features of the resulting acoustic flow and the distribution of the activity of cavitation events in a sonochemical reactor with a 1.7 MHz radiator using various methods.

2. Description of the experimental setup and measurement method

The experiments were carried out in a sonochemical reactor made of plexiglass with a thickness of 3 mm in the form of a cuboid with dimensions of $170 \times 112 \times 112$ mm$^3$ (Fig. 2, (a) – (d)). The ultrasound source consisting of a piezoceramic membrane with a diameter of 25 mm with a resonant frequency of 1.7 MHz was located flush with the bottom of the reactor (Fig. 2, №. 4). The piezoceramic emitter was connected to an ultrasonic generator with a nominal power of 30 W.

To study the features of the acoustic flow that occurs in the liquid under the influence of the ultrasonic source, the method of tracer and fluorescent imaging was used. The technique of tracer visualization was as follows. A mixture of light-reflecting polyamide particles with neutral buoyancy was introduced into the liquid, 60% of particles had a size of 50 $\mu$m, and the remaining 40% had a size of 80 $\mu$m. A laser sheet based on a 55 W TTL laser with a wavelength of $\lambda = 445$ nm was used to visualize the particles.

For fluorescence imaging, an aqueous solution of the dye Rhodamine-B at a concentration of 2 mg/l was used, the movement of which was recorded on a highspeed video camera Basler A504kc (Fig. 2, (a), №.5). The dye was illuminated using a laser sheet, which was created by a DPSS KLM-532 solid-state permanent laser with a wavelength of $\lambda = 532$ nm and provided the appearance of fluorescence.

To study the intensity of acoustic events in a sonochemical reactor, a technique based on thermocouple measurements was chosen, as in [9]. In the present experiments, a copper-constantane thermocouple was used, connected to the measuring complex (Fig. 2, a, №. 7) Termodat-38B1, the data from which were transmitted to the computer (Fig. 2, №. 1).

To measure the relative intensity of the acoustic radiation, a piezoceramic sensor KS0272 was used (Fig. 2, c, d, №. 3), the sensor diameter was 2 cm. The readings of this sensor were processed using an Arduino UNO microcontroller (Fig. 2, c, d, №. 2) and a personal computer (Fig. 2, №. 1).
Figure 2. Schemes of experimental installations: a - for fluorescent and tracer imaging; b - for implementing the method of thermocouple measurements; c,d - for measuring the intensity of acoustic exposure

Nine measurement points were selected for the study, one of which was located in the central area of the cell, four in the middle of the sides, and four more were located in the corners. The height from the bottom was varied and was 20, 75, 130 mm. The obtained measurement results were averaged over three experiments. A similar technique was used in [13].

3. Results

Under the action of a 1.7 MHz ultrasonic emitter in a sonochemical reactor, a localized acoustic current occurs in distilled water, resulting in the drift of the fluorescent substance. Figure 3, (a) shows the temporal dynamics of the dye drift. It can be seen that the dye at the initial stage has a low speed, but moving away from the emitter increases the speed of its movement. As can be seen from the photos, the rhodamine drift is centered strictly over the ultrasound source, in contrast to the flow observed from the 28 kHz ultrasound source from the work [9] (Fig. 3, b).

Figures 4, 5, 6 shows the combined tracer photos obtained for distilled water (Fig. 4), as well as solutions of NaCl with a concentration of 0.25 and 10% (Fig. 5, 6).

In the studied for liquids (Fig. 4), a stable acoustic jet is formed under the influence of ultrasound in the central region of the reactor. At the walls of the reactor, the appearance of vortex motion is observed.
Figure 3. Visualization of acoustic flow using Rhodamine-B dye: a – from 1.7 MHz ultrasound source; b – from 28 kHz ultrasound source

Figure 4. Combined tracer photos of the acoustic flow for H\textsubscript{2}O: a) \(t = [2 - 4]\) s, b) \(t = [4 - 6]\) s, c) \(t = [6 - 8]\) s from the beginning of the experiment

Figure 5. Combined tracer photos of the acoustic flow for NaCl 0.25%: a) \(t = [2 - 4]\) s, b) \(t = [4 - 6]\) s, c) \(t = [6 - 8]\) s from the beginning of the experiment
In a solution with a concentration of 0.25% NaCl (Fig. 5), the flow is different. The width of the acoustic jet increases in the area near the ultrasound source. When the NaCl concentration increases to 10% (Fig. 6), an even greater change in the flow pattern occurs.

The results of measuring the intensity of the acoustic impact by the sensor are plotted on the photos of the acoustic currents shown earlier. Figure 7, a) shows the results obtained for distilled water, b) for distilled water with a NaCl content of 10%, c) for distilled water with a NaCl content of 15%.

It can be seen that the addition of salt leads to a displacement of the area of increased pressure closer to the ultrasonic source. For example, in figure 7, (b), the maximum ultrasonic exposure is shifted to the ultrasound source, while in the case of distilled water, the maximum values are located symmetrically in the upper and lower parts of the reactor directly above the ultrasound source. Thus, an increase in the salt content changes the acoustic impedance of the system under study, thereby greatly changing the appearance of the resulting flow.

![Figure 6](image1.png)

**Figure 6.** Combined tracer photos of the acoustic flow for NaCl 10%: a) $t = [2-4]$ s, b) $t = [4-6]$ s, c) $t = [6-8]$ s from the beginning of the experiment

The results of the study of the intensity of acoustic events over the ultrasound source are shown in the figure 8. On the Y axis, the temperature is indicated in °C, $X$ is the time in sec, and on the top of the graphs (a) – (c), the height above the ultrasonic emitter in cm, over which the temperature was studied, is indicated. Figure 8, (d) shows the average one-minute thermocouple readings in a single experiment in the region above the ultrasonic source.

![Figure 7](image2.png)

**Figure 7.** The results of measuring the intensity of the vibration effect applied to the combined photos of acoustic flows: a - distilled water; b - NaCl 10%; c - NaCl 15%
Figure 8, (a) shows that the greatest intensity of cavitation events is observed in the case of distilled water in the region located near the surface of the liquid at a height of 15 – 16 cm. For a liquid with 0.25% NaCl content, the region of the highest intensity of acoustic events is shifted closer to the ultrasound source and is located at a height of 3 – 4 cm above the ultrasound source. This distribution of the intensity of cavitation events is obviously related to the change in the system impedance, the formation, dynamics, and coalescence of cavitation and vapor-gas bubbles in the volume of the sonochemical reactor.

Figure 8. Dependence of the intensity of cavitation events: a - distilled water; b - NaCl 0.25 %; c - NaCl 10 %; d - the average value for distilled water, for a solution of NaCl 0.25 % and for a solution of NaCl 10 %

4. Conclusions

For a sonochemical reactor with a 1.7 MHz ultrasonic source, in water and NaCl solutions, experimental studies were carried out: the type of emerging flows, using the method of tracer and fluorescent imaging; relative acoustic pressure, using a vibration sensor; the intensity of cavitation processes using thermocouple measurements.

The results obtained during experiments using tracer imaging showed an increase in the width of the acoustic jet in the region above the ultrasonic source when adding NaCl.

It is shown that with an increase in the salt concentration in the liquid the intensity of vibrations created by the ultrasonic source in the liquid decreases with an increase in the distance from the ultrasonic source.
This is due to a sharp change in the physical and chemical parameters of the liquid and an increase in the acoustic impedance for such media.

In addition, the addition of NaCl has an effect on the intensity of acoustic events. Thus, for an ultrasound source with a frequency of 1.7 MHz, in distilled water, using the thermocouple method, it is shown that the greatest intensity of cavitation events is observed at the surface of the liquid. For solutions containing 0.25 and 10 % NaCl, the maximum intensity of acoustic events decreases, shifting to the region near the ultrasonic emitter.

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