Regulation of bubbles ascending speed in water

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Abstract. The paper presents the result of the study of various methods of controlling the rate of ascent of air bubbles in water, such as the addition of surfactants, as well as the imposition of vibration. The ascent rate was estimated by the photometric method. It is shown that with increasing bubble sizes, an increase in the ascent rate is first observed, and then after reaching a maximum, the speed may begin to fall. This is due to the increase in resistance to the movement of the bubble due to the distortion of its shape. The additional imposition of vibroacoustic effects significantly improves the hydraulic properties of air bubbles as they ascend. It is shown that there is a vibration-acoustic effect and a mechanical effect of the piston on air bubbles and flotation complexes. The authors show that at the same time, a key role in the efficiency of the process of intensification of ascent is rendered by the time of acoustic impact.

1. Introduction
The movement of gas bubbles in a liquid is used in many modern technological processes [1, 2, 3]. In particular, the ascent of air bubbles plays an important role in flotation water purification [4, 5]. One of the main parameters describing the motion of a bubble in a liquid is the ascent rate. This follows from the multistage model of flotation [6, 7]. According to it, the flotation process, taking into account the coalescence of flotation complexes, proceeds as shown in figure 1 and is described by the following system of equations:

\[
\begin{align*}
\frac{d}{dt} C_A &= -K_1 C_A + K_2 C_B - K_6 C_A + K_5 C_C \\
\frac{d}{dt} C_B &= K_1 C_A - K_2 C_B - K_3 C_C - K_7 C_B + K_8 C_D \\
\frac{d}{dt} C_C &= K_3 C_B - K_4 C_C + K_6 C_A - K_5 C_C - K_9 C_D - K_{10} C_C \\
\frac{d}{dt} C_D &= K_7 C_B - K_8 C_D - K_9 C_D + K_{10} C_C 
\end{align*}
\]

(1)
with initial conditions

\[ C_A(t) + C_B(t) + C_C(t) + C_D(t) = C_0; \quad C_A(0) = C_0; \quad C_B(0) = 0; \quad C_C(0) = 0; \quad C_D(0) = 0, \]

where

- \( A \) — the initial state of the particles;
- \( B \) — the state of sticking and fixing of the particles on the bubbles;
- \( C \) — state of particles in the foam layer;
- \( C_A, C_B, C_D, C_C \) — concentration of particles in the states \( A, B, D \) and \( C \), respectively;
- \( K_1 \) is the constant of formation of the flotation complex;
- \( K_2 \) is the decay constant of the flotation complex;
- \( K_3 \) — the transition constant of the flotation complex in the foam layer;
- \( K_4 \) is a constant characterizing the loss of the flotation complex from the foam layer;
- \( K_5 \) is a constant characterizing the precipitation of particles of the solid phase from the foam layer;
- \( K_6 \) is a constant characterizing the probability of the transition of particles of a solid phase from a liquid to a foam;
- \( K_7 \) is the transition constant of flotation complexes to the enlarged flotation complex, due to their coalescence, and \( K_8 \) is a constant characterizing the disintegration of the enlarged flotation complex into smaller ones;
- \( K_9 \) — the transition constant of the enlarged flotation complex in the foam layer, and \( K_{10} \) — a constant characterizing the loss of the enlarged flotation complex from the foam layer.

One of the most difficult tasks in this case is to determine the kinetic constants of the flotation process and for each of them there are different ratios for different cases [8]. The constant \( K_3 \) in the general case can be determined on the basis of the following relationship:

\[ K_3 = \frac{\nu_{BC}}{h}, \]

where

- \( \nu_{BC} \) — float complex ascent rate [9];
- \( h \) — the distance from the aeration zone to the foam layer (the depth of the flow chamber).

Thus, ultimately, it is the ascent rate that determines such significant characteristics of the flotation apparatus as the overall dimensions and the total time of the water purification process [10].

At the present time, quite often in the practice of water purification, various reagents are used [11, 12, 13, 14], in particular, surface acting agents (SAA), which may affect the rate of ascent of bubbles. For example, ion flotation is based on the process of raising a flotation complex formed by an SAA molecule, an air bubble, and an ion of a pollutant [15].

Literature devoted to the consideration of this issue quite a bit [16]. In addition, published data are controversial. In this regard, an urgent task is the experimental determination of the rate of ascent of air bubbles in water containing SAA.

However, it should be noted that this method has several significant drawbacks, the main ones being the additional pollution of SAA water, as well as the difficulty in selecting the type of surfactant and dosing the required amount of it. Therefore, it is proposed to investigate the method of vibroacoustic effects [17, 18, 19] to achieve the desired result.
2. Methods and materials

2.1. SAA research impact

To determine the nature of the effect of SAA on the rate of ascent of air bubbles of different sizes, it is necessary to solve the following problems:

1. Getting a solution of water with a given concentration of SAA.
2. Measuring bubble size.
3. Measure the speed of ascent of the bubble.

The listed tasks determined the choice of means and methods of measurement. An electronic balance and a set of volumetric flasks of various sizes were used to prepare the SAA solution of the desired concentration. The size of the bubble was determined using photo and video. Measurement of the ascent rate was carried out indirectly through the time the bubble passes a specified distance. The time was recorded using an electronic stopwatch.

The experimental setup is a transparent cylindrical column 1, mounted on a stand 2 (figure 2). At the bottom of the column installed aerators 3, connected to the compressor 4 through the valve system. Inside the column there is a measurement scale of 5, and on the outer part there are levels of the beginning and end of the calculated section of the column (the distance between the marks H = 600 mm). On a tripod 6, a video camera 7 connected to a computer 8 is installed in front of the column. To improve the quality of shooting, the installation also has an additional light source 9.

In order to analyze the effect of SAA on the rate of ascent of bubbles, it seems advisable to compare the values of velocity in distilled water, tap water and, finally, in water containing SAA in various concentrations. As SAA in this work, relatively frequently used substance OP-10 according to GOST 8433–81 is used. The tests were carried out for the following concentrations: 1, 5, 10, 15, 20 mg/l. In this case, the preparation of the SAA solution of the desired concentration should be carried out immediately before the start of the experiment in order to avoid undesirable consequences of its aging (for example, micelle formation).

The experiment was carried out as follows. The column was filled with the prepared liquid. A compressor was turned on, and with the help of valves, a mode is set in which bubbles of approximately the same size were formed. Using different aerators and adjusting the gas flow, we managed to get bubbles of several sizes. The ascent time measurements were taken separately for each
bubble size obtained. Moreover, to improve the accuracy of measurement was repeated ten times. With the help of a stopwatch, the time of movement of the bubble selected for observation from the lower to the upper mark was detected. A chamber connected to a computer was used to determine the size of the bubble. It allows not only to monitor the movement of bubbles in real time, but also to take pictures of them against the background of the measurement scale inside the column. A visual comparison of a bubble in a photo with a unit of measurement gives the desired size. Regulation of distance, angle of view and light makes it possible to achieve better quality photos, and therefore increase the accuracy.

After carrying out the required number of experiments, the obtained data were processed. According to the known distance and time, the speed of ascent of the bubble was calculated, and according to the photo - the size and shape. Examples of photographs obtained during the experiments are shown in figure 3.

![Figure 3. Photos of pop-up bubbles of various sizes: a) 1.5 mm; b) 3 mm; c) 4 mm.](image)

2.2. Investigation of the effects of vibroacoustic effects

To determine the effect of vibroacoustic effects on the rate of ascent of air bubbles of various sizes, the following tasks were solved:

1. The choice of the optimal design of the laboratory setup.
2. Measuring bubble size.

The installation consists of a column 3 with a diameter of 110 mm, made of fibreglass. An aerator 5 is fixed in the column. The vibrator 1 by means of thrust drives the piston 4, which in turn is immersed to some predetermined depth in the column. The piston is a plate of various shapes, made of fiberglass. The vibrator is powered by a power amplifier, the signal to which is fed through a generator. The signal is sinusoidal.

The level of filling the column with water was equal to the number multiple of the diameter of the column and ranged from 3 to 5 diameters of the column.

In total, the installation was assembled in four different ways: when assembling according to scheme A, the aerator is located at the very bottom of the column; the piston is either directly above the aerator, or at some distance from it. The principal difference of scheme B is that the aerator is located on top of the piston. When the installation is switched on according to the scheme, the aerator is directly subjected to vibration, which is connected to the vibrator with the help of thrust. The piston in this scheme is missing. Scheme D is fundamentally different from the previous three; in this case, the column assembly with the aerator is attached directly to the vibrating table. In this case, the entire column with a liquid and a working aerator in it is subjected to vibroacoustic effects. When conducting experiments, aerators of various different types and designs were used: ceramic aerators of three sizes, two self-made aerators assembled from rubber hoses with pores of different sizes. The diameter of the bubbles ranged from 0.5 to 10 mm, depending on the type of aerator. Air was supplied to the aerators by means of two types of compressors differing in power. Both compressors have the ability to adjust the amount of air supplied. Since at this stage of this work there was no task to quantify the results obtained, for each type of aerator three levels of air flow were established:
• Maximum air flow rate — the flow rate that could be maximally obtained for this type of aerator.
• Average air flow is the flow at which the bubbles are as evenly distributed as possible over the cross-sectional area of the column.
• Minimum air flow rate - flow rate at which bubbles rise in one jet with a minimum distribution over the sectional area.

The level of consumption was limited not only by the capacity of the compressor and the pore diameter of the aerator, but also to the fact that there was some uniformity in the size of the bubbles for each level of air flow.

![General installation scheme](image)

**Figure 4.** General installation scheme: 1 – pre-amplifiers; 2 – compressor; 3 – aerator; 4 – piston; 5 – column; 6 – hydrophone; 7 – accelerometer.

The general setup diagram is presented in figure 4. The results of the experiments were recorded. As in the case of surface-active substances, photometry was used. But in addition, with the help of an accelerometer mounted on a column and a hydrophone immersed in the water layer, its own amplitude-frequency spectrum was measured. For this, a 2-channel narrow-band real-time analyzer from Brüel&Kjaer was used. One channel, with an accelerometer 7, mounted on the body of the column, was the driver, and the second (with hydrophone 6) was measuring.

### 3. Results and discussion

Thus, at first, the ascent rate of bubbles of various sizes in distilled water, tap water, and water containing different concentrations of SAA were obtained. The results of measurements and calculations are showed in table 1.

Analyzing the results of the experiments, it can be noted that with an increase in the bubble size, an increase in the ascent rate is first observed, and then after reaching the maximum, the speed may begin to fall. This is due to the increase in resistance to movement of the bubble due to the distortion of its shape. With an increase in the concentration of SAA in water, the rate of ascent of bubbles of the same size decreases. This is due to the fact that SAA molecules are adsorbed on the surface of the bubbles, thereby increasing resistance.

It is worth noting that when exposed to vibration with frequencies from 10 to 10,000 Hz, the wavelength changes from 150 m to 15 cm, respectively, and the direction of sound propagation is two-sided (both downward from the piston and upward). Thus, from this point of view, the change in the relative position of the piston and the aerator, as well as the distance between them, should not have any significant effect. However, during the experiments, various effects were discovered. This is due to the fact that the air bubble, leaving the aerator, falls on a vibrating piston, which has on them in addition to the acoustic mechanical effect. Thus, there is a vibration-acoustic effect on air bubbles and
flotation complexes and the mechanical action of the piston. Changing the distance between the piston and the aerator increases the time it takes for a bubble or flotation complex to travel from the aerator to the piston. And the duration of the acoustic impact may be decisive to achieve the desired result.

| No. | No.  | Ascending speed, m/sec, bubble diameter, mm |
|-----|-----|------------------------------------------|
| 1   | 0.099 | 0.117 | 0.221 | 0.205 |
| 2   | 0.0106 | 0.233 | 0.227 | 0.236 |
| 3   | 0.105 | 0.174 | 0.193 | - |
| 4   | 0.155 | 0.168 | - | 0.203 |
| 5   | 0.062 | 0.160 | - | 0.209 |
| 6   | 0.130 | 0.193 | - | - |
| 7   | 0.085 | 0.173 | - | 0.185 |

The number in the first column correspond to the experiment in the following fluids: 1 – distilled water; 2 – tap water; 3 – water with a concentration of SAAC = 1 mg/l; 4 – the same with C = 5 mg/l; 5 – the same with C = 10 mg/l; 6 – the same with C = 15 mg/l; 7 – the same with C = 20 mg/l.

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