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THE PHENOMENON OF RESONANCE IN GAS-STEAM BUBBLES

Introduction

In the basis of many advanced industrial technologies there are such thermodynamic processes occurring on the surface of gas-particle bubbles as absorption [16], aeration [13], bubbling [9], vacuum distillation [5], degassing [3], boiling [18], cavitation [12], the production of heat-insulating materials by the method of blowing [19], gas hydrating [11], and many others.

Active studies of the bubbles effect on sound vibrations were carried out to optimize the sonar operation. Existing literature [1, 4] highlights the issue of the damped oscillations at frequencies from 4 kHz to 150 kHz in seawater at different depths. Another direction of research was caused by the need for the use of cavitation [14]. The study of fluid degasification by cavitation method was carried out at frequency from 10 kHz to 1 MHz.

In most cases, bubbles oscillation is damping. However, definitely during these oscillations, the most intense heat and mass exchange processes on the bubbles surface are observed. In the course of oscillation, there is a very rapid change in the thermodynamic parameters of the system "gas bubble-liquid". The urgency of the study of heat and mass transfer processes dynamics on the oscillating gas bubble surface is due to the need to optimize various technological processes.

Analysis of recent research sources and publications

To analyze the dynamics of steam bubbles oscillations, the Relay-Plasset equation is widely used [7]. To determine the pressure inside the vapor bubble, the Clapeyron-Clausius equations are often used [15], or the process is considered to be adiabatic [2]. According to other scientists, the processes inside the oscillating bubble are not limited only to the phase transition or the lack of heat exchange on the bubble surface. In [8, 10], the mathematical formulation of the problem is more complete. In addition to the Rayleigh-Plasset equation, it includes the Van der Waals equation for determining the pressure inside the gas-particle bubble and allows to calculate the temperature of the gases inside the bubble on the basis of the first law of thermodynamics. Also, the mathematical model is supplemented by the transfer of heat and mass across the boundary of the bubble. However, this mathematical model is for bubbles formed as a result of cavitation and within highly liquefied gas.

To simulate the oscillation processes of the vapor-gas bubbles, it is necessary to consider the possibility of dissolving gases in the liquid and water vapors condensing on the surface of the gas-particle bubble. The process of oscillations damping is determined not only by the liquid viscosity, but also by the rate of heat and mass transfer processes near the bubble surface which, in turn, depends on the temperature and pressure of the gas mixture inside the bubble.

Setting objectives

The purpose of this work is to study the effect of sound vibrations of different frequencies on the thermodynamic processes occurring in the vapor-gas environment of the oscillating bubble. To achieve this goal, the following tasks were identified:

- to supplement the mathematical model of a gas bubble in a fluid by an oscillation generator;
- to perform calculations of transient thermodynamic processes inside oscillating gas bubbles of different sizes under conditions of acoustic influence on a liquid;
- to conduct in-person experiments for confirming the calculated resonance frequencies and to observe the phenomenon of bubbles resonance.

Mathematical model of gas-particle bubbles oscillation

To obtain estimated data about the influence of acoustic vibrations on thermobaric characteristics of a gas-bubble, the mathematical model containing the following simplifying assumptions was used:

- gas bubble is spherical;
- fluid is viscous and incompressible;
- within the gas bubble there is a mixture of gases (air and friable vapors), which mass can change as a result of mass transfer processes at the boundary of the bubble;
- the gases inside the bubble are considered as real gases (considering the Van der Waals forces).

Equations describing the behavior of a gas – particle bubble in the transition to a new state of thermodynamic equilibrium are considered [20].

$$\frac{d\dot{R}}{d\tau}=\frac{P_{B(\tau)}-P_{\infty}}{\rho_r R}-\frac{1.5}{R}\dot{R}^2-\frac{4\mu_r}{\rho_r\cdot R^2}\dot{R}-\frac{2\sigma_r}{\rho_r\cdot R^2} \tag{1}$$

$$\frac{dR}{d\tau}=\dot{R} \tag{2}$$

$$P_B=P_w+P_a \tag{3}$$

$$P_w=\frac{R_\mu T}{\dfrac{\mu_w}{\rho_w}-b_w}-\rho_w^2\frac{a_w}{\mu_w^2},\qquad P_a=\frac{R_\mu T}{\dfrac{\mu_a}{\rho_a}-b_a}-\rho_a^2\frac{a_a}{\mu_a^2} \tag{4}$$

$$\frac{d\rho_w}{d\tau}=\frac{3}{R}\left(I_w-\rho_w\frac{dR}{d\tau}\right),\qquad \frac{d\rho_a}{d\tau}=\frac{3}{R}\left(I_a-\rho_a\frac{dR}{d\tau}\right) \tag{5}$$

$$\frac{dT}{d\tau}=\frac{3}{R\left(c_w\rho_w+c_a\rho_a\right)}\left[q-P_B\frac{dR}{d\tau}\right] \tag{6}$$

$$q=\left[\left(\frac{1}{6}\rho_w\bar{v}_{w(T)}+I_w\right)c_w+\left(\frac{1}{6}\rho_a\bar{v}_{a(T)}+I_a\right)c_a\right]\left(T_{(R,\tau)}-T\right) \tag{7}$$

$$\bar{v}_{w(T)}=\sqrt{8R_\mu T/\mu_w\pi}\quad\text{and}\quad \bar{v}_{a(T)}=\sqrt{8R_\mu T/\mu_a\pi} \tag{8}$$

$$I_w=-\frac{D_w P_w}{R\Gamma_w}\quad\text{and}\quad I_a=-\frac{D_a P_a}{R\Gamma_a} \tag{9}$$

$$\frac{\partial\left(\rho_r c_r T_{r(x,\tau)}\right)}{\partial \tau} = \frac{1}{x^2}\frac{\partial}{\partial x}\left(\lambda_r x^2 \frac{\partial T_{r(x,\tau)}}{\partial x}\right) - \dot{R}\frac{\partial\left(\rho_r c_r T_{r(x,\tau)}\right)}{\partial x} \tag{10}$$

$$-\frac{\partial\left(\lambda_r T_r\right)}{\partial x}(x = R, \tau) = -q \tag{11}$$

$$-\frac{\partial\left(\lambda_r T_r\right)}{\partial x}(x = \infty, \tau) = 0 \tag{12}$$

$$T_{r(x,\tau=0)} = T_0 \tag{13}$$

$$P_\infty = P_0 \sin\left(\frac{2\pi}{\Pi}\cdot\tau\right) \tag{14}$$

where: P_w, P_a – partial pressure, respectively, of water vapor and air, Pa; R – radius of gas bubble, m; τ – time, s; P_B – pressure of the gas mixture inside the bubble, Pa; P_∞ – pressure in a liquid, Pa; ρ_r – liquid density, kg/m^3; μ_r – is the dynamic viscosity of the liquid, Pa·s; σ_r – coefficient of liquid surface tension, N/m; ρ_w, ρ_a – density of water vapor and air, kg/m^3; $R_\mu = 8314$ – universal gas constant, J/(kmol·K); μ_w – is the molecular weight of water, kg/kmol; μ_a – is the molecular mass of air, kg/kmol; T – temperature of the gas mixture in the bubble, K; a – is the constant of Van der Waals, (H·m^4)/mol^2; b – is the constant of Van der Waals, m^3/mol; I_w, I_a – is the mass of water vapor and air diffusing through unit of bubble surface per unit time, kg/(m^2·s); c_w, c_a – heat capacity of water vapor and air, J/(kg·°C); q – specific heat flow directed from the wall to the gas medium of the bubble, W/m^2; $\bar{v}_{(T)}$ – the arithmetic mean velocity of gas molecules at a temperature T, m/s; D_w, D_a – coefficients of diffusion, respectively, of water vapor and air, m^2/s; Γ_w, Γ_a – Henry constants for water vapor and air, respectively (Pa·m^3)/kg; ρ_r – liquid density, kg/m^3; c_r – heat capacity of the liquid, J/(kg·°C); τ – is the time coordinate, s; x – is the spatial coordinate, m; λ_r – liquid effective heat conductivity coefficient, W/(m·°C); ∂V – elemental volume, m^3.

The system of equations (1)÷(14) can be solved using numerical methods, for example, the Rung-Kutta method of the 4th order [6, 17].

The research results of the effect of harmonic pressure variations on thermodynamic processes in bubble gas environment

Theoretical studies. According to the proposed mathematical model, the calculations of air bubble oscillations of various sizes in water were performed. The water temperature is 20°C, atmospheric pressure. To match the experimental data, the amplitude of the sound oscillations pressure is 5 kPa. The mathematical modeling results of bubble parameters with various sizes are shown in Figures 1÷4.

Figure 1 shows that each bubble size corresponds to its own resonance frequency, which depends on the thermodynamic parameters of the gas-vapor mixture within the bubble and the surrounding liquid layers. At the given conditions, the resonant frequency of bubbles can be determined by the approximation formula, Hz

$$f_R = \frac{5.465}{d} \tag{15}$$

where d is the diameter of the bubble, m.

After the bubble enters into the resonance, its oscillation amplitude is stabilized at the level 30÷50% of its radius. It is due to the energy balance alignment: the amount of energy supplied to the sound vibrations is equal to the energy loss for friction in water, heat and mass transfer near the bubble surface.

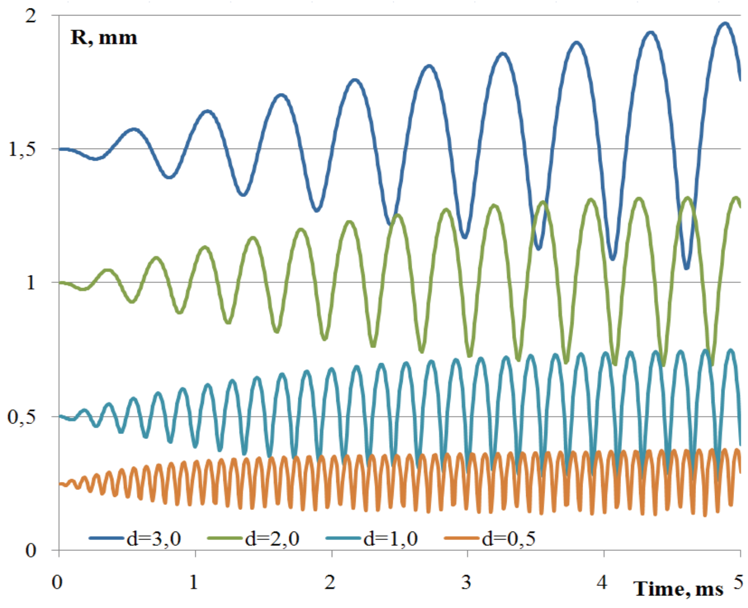

FIGURE 1. *Changing the bubbles radius of various sizes under resonance conditions*

The analysis of the bubble wall velocity (Fig. 2) shows that it can reach 6 m/s. It is approximately 1000 times more than the wall velocity during bubble damping oscillations. Greater speeds are observed only in cavitation bubbles during maximum compression.

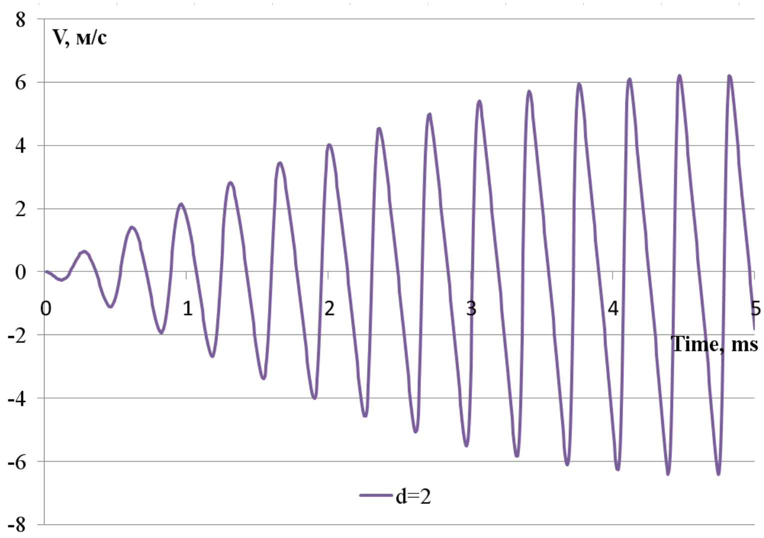

FIGURE 2. *Radius bubble change velocity (diameter 2 mm)*

At the same time, but in the antiphase to the movement of the bubble walls, there is a change in its internal pressure (Fig. 3). Calculations show that in the half-lives of compression, the internal bubble pressure can exceed the ambient pressure three times. In the half-expanding pressure of the gas-vapor environment, the bubble decreases in comparison with the environmental pressure more than twice. Such fluctuations in pressure create the preconditions for the intensification of heat and mass transfer near the bubble surface.

Figure 4 shows the gas-vapor medium temperature regime of a resonating bubble. Relative to the initial value of temperature, fluctuations occur within the range of +13 to -7°C. Fluctuations in temperature on the bubble surface are shown in Figure 5. Despite the synchronous nature with fluctuations in the gas temperature within the bubble, the temperature regime of water surface is significantly different. Relative to the initial value, the temperature rises by 7.4°C, and decreases by only 1°C.

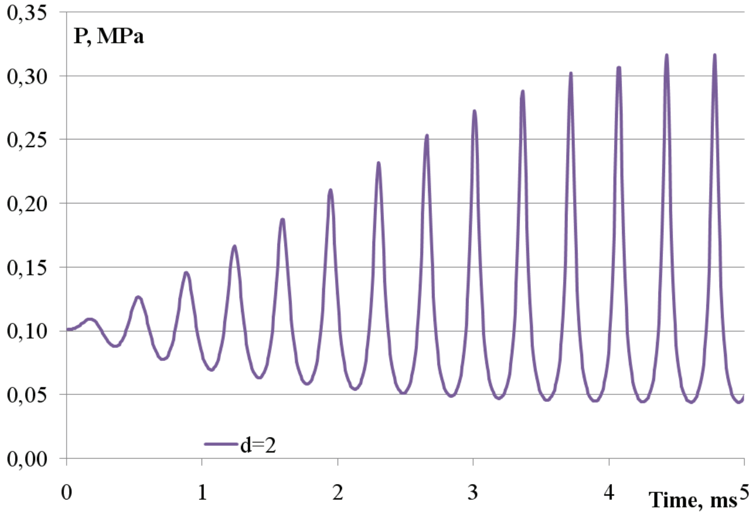

FIGURE 3. *Graph of gas pressure in a resonating bubble*

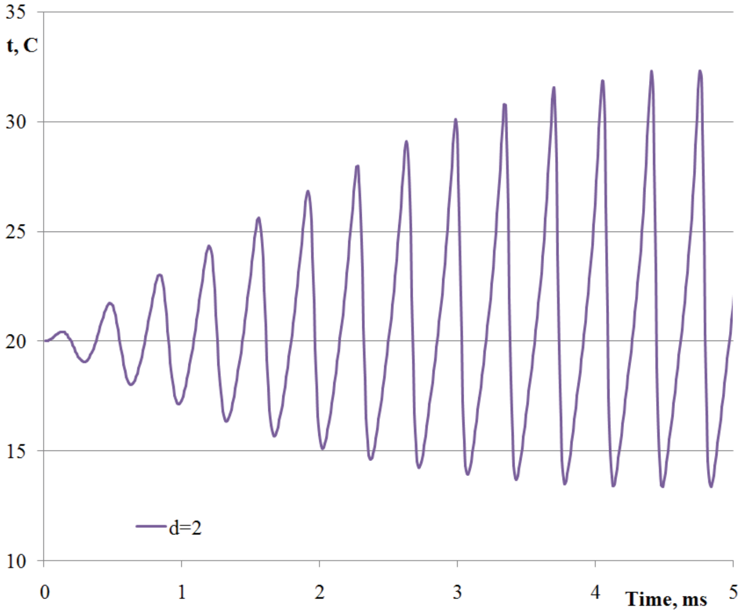

FIGURE 4. *Graph of gas temperature in a resonating bubble*

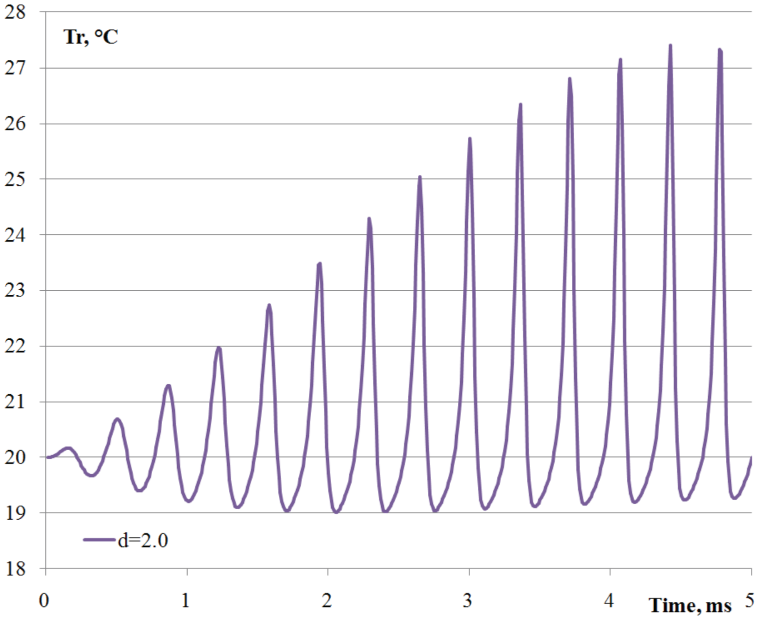

FIGURE 5. *The surface temperature of a resonating air bubble in water*

Figure 6 shows that despite considerable amplitude, fluctuations in the temperature of the liquid are practically damped to reach the 7th layer (about 7 microns from the surface). Apparently the reason for this is the oscillations high frequency.

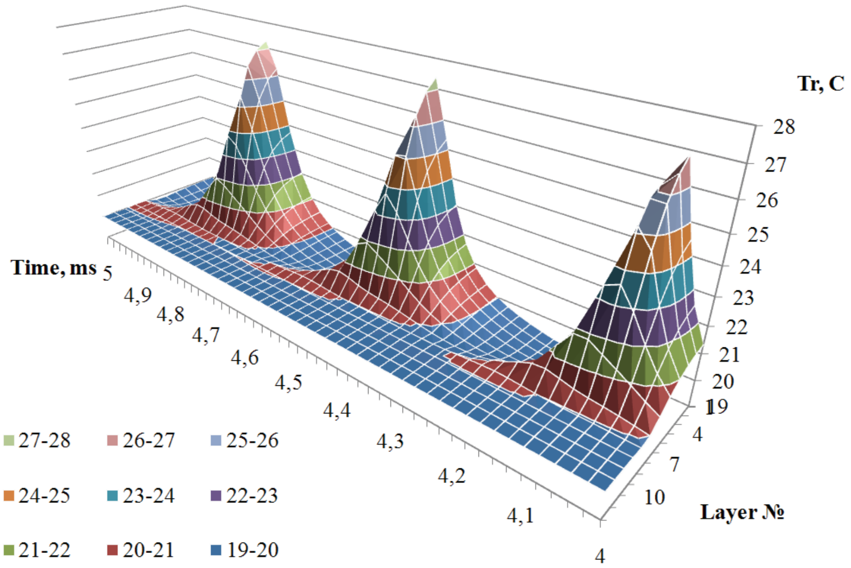

FIGURE 6. *Temperature of water layers around the resonate bubble*

Natural studies. For field observations of resonance processes in bubbles, a research equipment was assembled. Harmonic fluctuations in water were created using a piezoceramic resonator with a diameter of 27 mm. The resonator power was supplied from a variable-frequency multivibrator with amplifying output stage. In general, the multivibrator overlaps the frequency range from 280 Hz to 500 kHz. In experiments, the frequency of the output signal was determined using the electronic frequency meter F5311, and the shape was established with an oscilloscope of H313.

According to experimental data, in the frequency range of 2÷5 kHz, voltage applied to radiator was approximately 0.6 W. Considering the oscillator surface area, its specific power is 1047 W/m^2, which corresponds to the sound pressure in water P = 5.404 kPa (Fig. 7). This sound pressure is equivalent to a sound level of 168.6 dB. At frequencies above 100 kHz, there is a "collapse" of the radiator characteristics, the reason of which is the radiator protection system operation from the destruction.

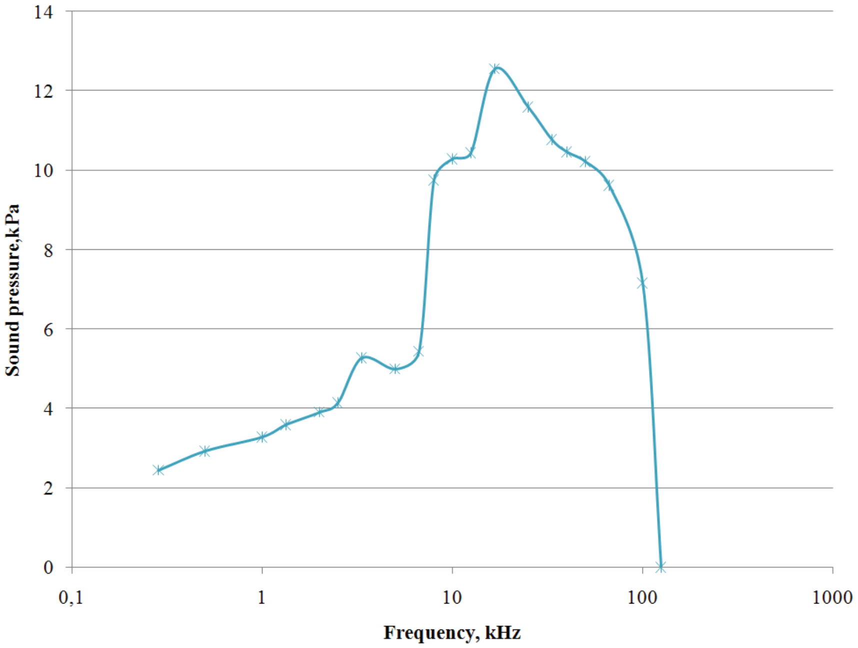

FIGURE 7. *Sound pressure that creates piezoceramic resonator in water*

To obtain bubbles of various sizes, water was brought into the tank under pressure. When bubbles of resonant size are in water (according to formula 15), they begin to oscillate and the sound total amplitude increases tenfold. A fragment of the sound track recording at the time of a bubble entry into resonance is shown in Figure 8. Compared with the estimated data, the time a real bubble needs to enter the resonance is 4-5 times larger.

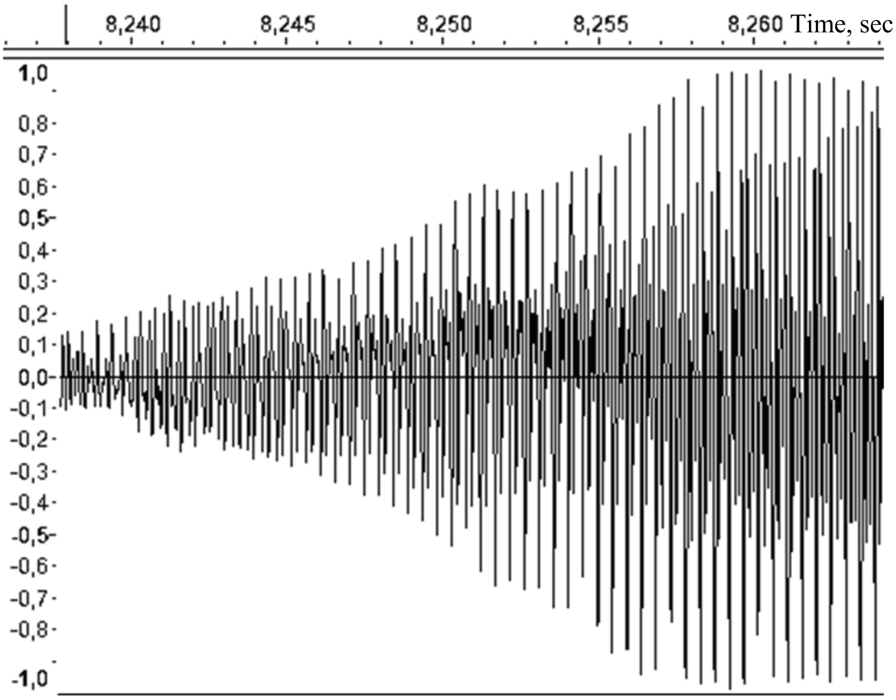

Figure 8. *A fragment of the sound track recording at the time of a bubble's entry into the resonance*

According to the results of field observations in clear water at resonance frequencies, bubbles are rapidly divided into a large number of small ones. Moreover, small bubbles are contained within the large (multibubble) with the surface tension forces.

Multibubbles begin to be formed at frequencies above 2 kHz and cease forming at frequencies above 3 kHz. The maximum activity is observed at frequency of 2.5 kHz, which corresponds to a diameter of bubbles of 2.3 mm. When reaching the maximum size, the multibubble can be divided into smaller ones (Fig. 9), may explode with the f small bubbles clouds formation, or may become a source of small bubbles that are constantly "detached" from the large and begin to "self" life in the fluid.

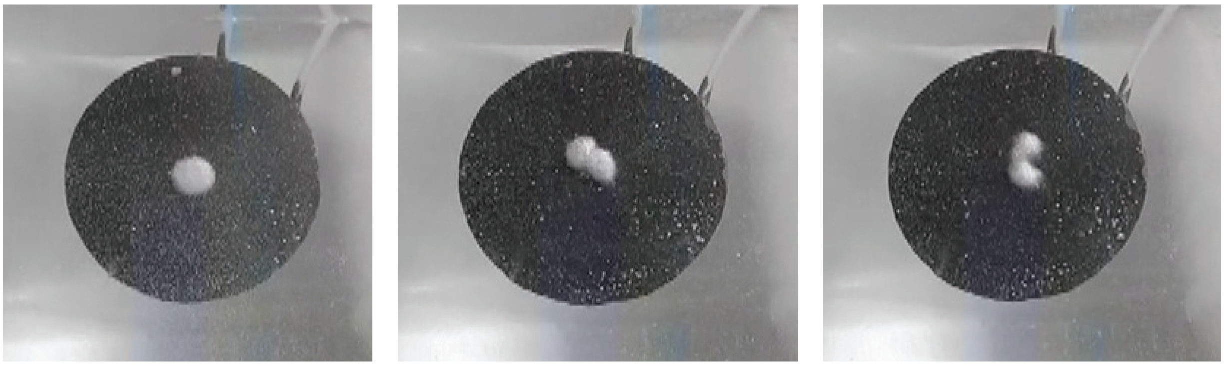

Figure 9. *Separation of a large multibubble into two smaller sizes (left to right video footage)*

Adding water to surfactants (surfactants) immediately expands the range of multibubble formation. They begin to appear at the frequency of 830 Hz and end up at the frequencies above 5 kHz. At the frequency of 2.5 kHz, the most active formation of bubbles millions is observed. With the use of surfactant, the number of small bubbles in large one significantly increases. In the footage of the video there is a "blast" of such multibubble with the formation of microscopic bubbles cloud (Fig. 10).

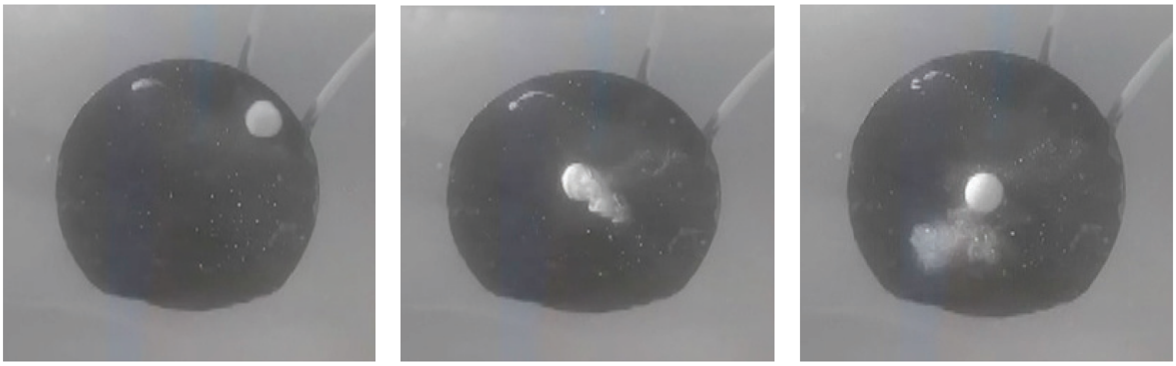

FIGURE 10. *Blast of multibubbles (left to right video footage)*

In general, experimental studies have confirmed the existence of gas bubbles resonance in water at estimated frequencies. In addition, it was possible to obtain multibubbles and a large number of bubbles of less than 0.1 mm.

Conclusions and perspectives

1. As a result of mathematical modeling, the possibility of resonance in gas-particle bubbles of different sizes is established. The resonance frequencies and thermodynamic parameters of the gas-particle bubble under resonance conditions are determined.
2. The existence of bubbles resonance at estimated frequencies was shown by experiments. Field Studies have shown that resonance vibrations of bubbles are accompanied by the formation, growth and destruction of multibubbles. The prolonged action of sound waves at resonant frequencies results in the formation of a very large number of bubbles in the volume of liquid in the size of less than 0.1 mm.
3. The use of surfactant significantly expands the frequency range of multibubble formation and increases the number of small bubbles in the middle of a large one.
4. Application of bubbles resonance has great prospects for intensification of many technological processes based on heat and mass transfer processes on the boundary of liquid-gas.

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