Запропоновано математичну модель для розрахунку резонуючих газопарових бульбашок. Досліджено вплив звукових хвиль на осциляцію бульбашок в умовах резонансу. Отримано форму та амплітуду коливань стінки для бульбашок різного розміру на резонансних частотах. Визначено швидкість руху стінки та внутрішній тиск бульбашки в умовах резонансу. Наведено результати натурних спостережень за газопаровими бульбашками в умовах дії звукових хвиль

Ключові слова: звукові хвилі, газопарова бульбашка, резонансна частота, мультибульбашка, поверхнево активні речовини

Предложена математическая модель для расчета резонирующих газопаровых пузырьков. Исследовано влияние звуковых колебаний на осцилляцию пузырьков в условиях резонанса. Получена форма и амплитуда колебаний стенки для пузырьков различного размера на резонансных частотах. Определены скорость движения стенки и внутреннее давление пузырька в условиях резонанса. Приведены результаты натурных наблюдений за газопаровыми пузырьками в условиях влияния звуковых колебаний

Ключевые слова: звуковые волны, газопаровой пузырек, резонансная частота, мультипузырек, поверхностно-активные вещества

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RESEARCH INTO RESONANCE PHENOMENA IN GAS-VAPOR BUBBLES

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1. Introduction

Thermodynamic processes that occur on the surface of gas-vapor bubbles, such as absorption [1], aeration [2], bubbling [3], and vacuum distillation [4], are at the heart of many advanced industrial technologies. Thermal and mass exchange processes, which are the basis of degassing [5], boiling [6[, cavitation [7], obtaining gas hydrates [8] and many others also occur on the interphase surface of bubbles.

Active research into the influence of bubbles on sound oscillations was carried out to optimize the operation of hydrolocators. In the available literature [9], the issue of damping of oscillations with frequencies from 4 kHz to 150 kHz in sea water at different depths was highlighted. Another direction of research was caused by the necessity of application of cavitation [10, 11]. Studies of fluid degassing by the cavitation method were carried out starting with the frequency of 10 kHz to the frequency of 1 MHz

Oscillations of bubbles have a damping character in most cases. However, the most intense heat and mass exchange processes on the surface of bubbles were observed during these oscillations. A very quick change of thermodynamic parameters of the “gas bubble–fluid” system occurs during oscillation. The relevance of the study into dynamics of mass exchange processes on the surface of an oscillating gas bubble is explained by the necessity for optimization of various technological processes.

2. Literature review and problem statement

The Rayleigh-Plesset equation is often used for analysis of the dynamics of oscillations of vapor bubbles. The analysis of fluid flow with lots of bubbles of different dimensions, considered in [12], is also based on the solution of this equation. Given the large amount of calculation of a three-dimensional model, the authors did not consider the phase transition processes either on the surface of the fluid, nor in the middle of bubbles. The Clapeyron-Clausius equation was applied for determining pressure under conditions of constant boiling [13]. However, in the face of oscillatory pressure changes, it is necessary to consider that the periods of boiling alternate with the periods of diffusive mass exchange. In addition, such problem statement does not consider partial pressure of gases that do not participate in phase transitions.

Quite often, in order to determine pressure inside cavitation bubbles, the process is considered to be adiabatic [14]. However, this assumption is only possible for separate stages in the development of a cavitation bubble when the wall velocity exceeds one hundred meters per second. In the work by V.R. Kulinchen [15], mathematical problem statement takes into account phase transition and heat exchange near the surface of an oscillating bubble. However, this model is designed for the bubbles that are formed as a result of cavitation and inside of which there is greatly rarified gas.

The mathematical model, considered in [5], contains a model of the source of harmonic oscillations but pressure of saturated vapor inside a bubble is accepted as constant, and only bubbles of critical dimensions are considered. F. Hegedűs in [16] considered a single spherical gas bubble that contains both non-condensed gas and vapor, but did not take into consideration phase transition processes on the surface of a bubble.

Comparison of three mathematical models of motion of a cavitation bubble in the acoustic field was performed in paper [10]: a polytropic model, a model ideal gas and radially distributed thermodynamic parameters inside a bubble. A description of mass transfer and phase transition processes is also missing in these models, the frequency of acoustic oscillations, assigned by the author, is significantly lower than the resonance one. Paper [1] presents a physical-mathematical model of heat and mass exchange and gas absorption on the surface of a bubble. The obtained results of calculation show a considerable influence of gas dissolution on the temperature mode of the gas phase of a bubble, but do not consider oscillatory character of a bubble's motion velocity.

Analysis of the scientific literature shows that the study of resonance oscillations of bubbles in terms of acoustic impact should be not only interesting from the scientific point of view, but are also of great practical importance, since it is a way of intensification of heat and mass transfer processes for a variety of industrial technologies.

3. The aim and objectives of the study

The aim of present research is to study the influence of sound oscillations of resonance frequency of thermodynamic processes that occur in a gas-vapor medium of an oscillating bubble. This will make it possible to enhance effectiveness of absorption, aeration, to accelerate degassing of fluids, to reduce the negative impact of the boiling crisis and to optimize other technological processes.

To accomplish the set goal, the following tasks were determined:

– to supplement the mathematical model of a gas bubble in fluid with the source of sound oscillation, consider phase transition processes in the fluid, on the surface of a bubble and in the gas-vapor medium;

– to perform calculations of transient thermodynamic processes inside oscillating gas bubbles of different dimensions in terms of acoustic impact on the fluid;

– to analyze the effect of temperature on thermal-physical parameters of oscillating bubbles;

– to conduct field tests to prove the calculated resonance frequencies and observation of the phenomenon of bubbles resonance, to evaluate the influence of surfactants on oscillatory processes of bubbles.

4. Proposed mathematical model of gas-vapor bubbles oscillation

The mathematical model [17] was accepted as the basis for studying the influence of acoustic oscillations of the resonance frequency on the thermobaric characteristics of a gas-vapor bubble. This model was supplemented with relevant components in the equation (11) for the purpose of taking into account the thermal effect of phase transition processes on the surface of a bubble and gas dissolution. Equation (5) was changed in order to take into account mass transfer processes at condensation/evaporation of water vapor inside a bubble. Equation (14) was used for description of a source of harmonic pressure oscillations (acoustic oscillations). The model contains the following simplifying assumptions:

– a gas bubble is of spherical shape;

– a fluid is viscous and non-compressed;

– inside a gas bubble, there is a mixture of gases (air and water vapor), the weight of which may vary as a result of mass exchange processes both on the boundary of a bubble, and in its volume;

– gases inside a bubble are considered as actual gas (taking into account the van der Waals forces).

Let us consider the equations describing thermodynamic characteristics of a gas-vapor bubble during transition to a new state of thermodynamic equilibrium [17]:

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

$$\frac{dR}{d\tau}=\dot{R}+\frac{I_w}{\rho_r}, \qquad (2)$$

$$P_B=P_w+P_a, \qquad (3)$$

$$P_w=\frac{R_\mu T}{\frac{\mu_w}{\rho_w}-b_w}-\rho_w^2\frac{a_w}{\mu_w^2}$$

and

$$P_a=\frac{R_\mu T}{\frac{\mu_a}{\rho_a}-b_a}-\rho_a^2\frac{a_a}{\mu_a^2}, \qquad (4)$$

$$\frac{d\rho_w}{d\tau}=\frac{3}{R}\left(I_w-\rho_w\frac{dR}{d\tau}\right)+I_{wr}$$

and

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

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

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

$$\overline{v}_{w(T)}=\sqrt{8R_\mu T/\mu_w\pi}$$

and

$$\overline{v}_{a(T)}=\sqrt{8R_\mu T/\mu_a\pi}, \qquad (8)$$

$$I_w=\frac{2D_w}{R}\left(\rho_w^*-\rho_w\right)$$

and

$$I_a=-\frac{D_aP_a}{R\Gamma_a}, \qquad (9)$$

$$\frac{\partial\left(\rho_r c_r T_{r(x,\tau)}\right)}{\partial\tau}=$$

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

$$-\frac{\partial\left(\lambda_r T_r\right)}{\partial x}_{(x=R,\tau)}=-q-\frac{r_w}{4\pi R^2}\frac{dm_r}{d\tau}+I_a r_{ra}, \qquad (11)$$

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

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

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

where P_w, P_a are the partial pressures of water vapor and the air, respectively, Pa; R is the radius of a gas bubble, m; τ is the time, h, s; P_B is the pressure of a gas mixture inside a bubble, Pa; P_∞ is the pressure in fluid, Pa; ρ_r is the density of fluid, kg/m^3; μ_r is the dynamic viscosity of fluid, Pa·s; σ_r is the coefficient of surface tension of fluid, N/m; ρ_w, ρ_a are the densities of vapor and the air, kg/m^3; ρ_w^* is the densities of saturated water vapor, kg/m^3; R_μ is the universal gas constant, J/(kmol·K); μ_w is the molecular mass of water, kg/kmol; μ_a is the molecular mass of the air, kg/kmol; T is the temperature of gas mixture in a bubble, K; a is the Van der Waals constant, (N·m^4)/mol^2; b is the Van der Waals constant, m^3/mol; I_w, I_a are the mass of water vapor and air, that diffuse through a unit of the surface per unit of time, kg/(m^2·s); I_{wr} is the mass flow of water vapor that is condensed in gas medium of a bubble per unit of time, kg/(m^3·s); s_w, s_a are thermal capacity of water vapor of the air, J/(kg·°C); q is the specific thermal flow, directed from the wall to gas medium of a bubble, W/m^2; m_w is the mass of water that evaporates from the surface of a bubble in the known time interval, kg; r_w is the heat of the phase transition water–water vapor, J/kg; r_{ra} is the heat of air dissolution in water, J/kg; $\bar{v}_{(T)}$ is the arithmetical mean velocity of gas molecules at temperature T, m/s; D_w, D_a are the diffusion coefficients of water vapor in the air and of air in the water, respectively, m^2/s; Γ_a is the Henry constant for the air above the water surface, (Pa·m^3)/kg; ρ_r is the fluid density, kg/m^3; c_r is the thermal capacity of fluid, J/(kg·°C); T_r is the fluid temperature, K; x is the space coordinate, m; λ_r is the effective coefficient of fluid thermal conductivity, W/(m·°C); q_v is the voluminous power of sources or heat flows, W/m^3; T_0 is the initial fluid temperature, K; P_0 is the initial fluid pressure, Pa; A_P is the amplitude of pressure fluctuations, Pa; Π is the oscillation period, s;

Conditions for the occurrence of phase transitions. In the gas-vapor medium:

– if $T<T_s$, water vapor condensation occurs;

– if $T>T_s$ and $m_{wr}>0$, evaporation of water vapor condensate occurs. Hereinafter, T_s is the dew point temperature, K; m_{wr} is the mass of condensed water vapor in the gas-vapor medium in a bubble, kg.

At the boundary of a bubble (water surface):

– if $T_r>T_s$, water boils;

– if $T_r<T_s$, condensation of water vapor occurs;

– if $P_w^*>P_w$, diffusion of water vapor from the surface of a bubble to its gas-and-vapor medium;

– if $P_w^*<P_w$, diffusion of water vapor from the gas-vapor medium of a bubble to its surface.

In water:

– if $T_r<T_{w\text{-}i}$ and $m_{r(i)}>0$ ice formation occurs;

– if $T_r>T_{w\text{-}i}$ and $m_{r(i)}>0$ ice melting occurs. Here $T_{w\text{-}i}$ is the temperature of the phase transition water-ice; $m_{r(i)}$ is the fluid mass in the i-th layer; $m_{r(i)}$ is the ice mass in the i-th layer.

Approximations of thermo-physical quantities. A number of thermo-physical values of the mathematical model greatly depend on thermobaric conditions. Approximation formulas for such values were applied in the mathematical model to enhance calculation accuracy.

Dynamic viscosity of water, Pa · s

$$\mu_r=\frac{0{,}0017865}{1+0{,}0347t_r+0{,}000221t_r^2},$$

where t_r is the fluid temperature, °C.

Water density within the temperature interval of 0÷40 °C, kg/m^3

$$\rho_r=\frac{1000}{1+0{,}0000065\left(t_r-4\right)^2}.$$

Water density within the temperature interval of 40÷100 °C, kg/m^3

$$\rho_r=\frac{1000}{1+0{,}000022\left(t_r-4\right)^{1{,}66}}.$$

Coefficient of surface tension at the water-air boundary, N/m

$$\sigma_r=0{,}131\left(1-\frac{273+t_r}{647{,}2}\right).$$

Partial pressure of water vapors on the saturation line, Pa

$$P_w^*=620\ell^{18.9\left(1-\frac{273}{T}\right)}.$$

Dew point temperature, K

$$T_s=\frac{273}{1-\frac{\ln\left(P_w/620\right)}{18{,}9}}.$$

Heat of the phase transition water-vapor, J/kg

$$r_w=1000\left(3180+2{,}5\left(273+t_{r(x=R)}\right)\right).$$

Heat of air dissolution in the water, J/kg

$$r_{ra}=1000\left(549-6{,}3t_{r(x=R)}\right).$$

Thermo-physical parameters, which relatively little change within the calculation range of thermobaric conditions, are accepted as constant in the mathematical model, Table 1.

The system of equations (1)–(14) in the terms of phase transitions by approximated and constant thermal-physical magnitudes can be solved by using digital techniques, such as the Runge-Kutta method of the fourth order [18, 19].

Table 1

Constant thermo-physical quantities

Magnitude	Designation	Amount	Measurement unit
universal gas constant	$R\mu$	8314	J/(kmol·K)
molecular mass of water	μ_w	18,015	kg/kmol
molecular mass of air	μ_a	28,96	kg/kmol
thermal conductivity of water	λ_r	0,57	W/(m·°C)
specific thermal capacity of water	c_r	4187	J/(kg·°C)
specific thermal capacity of water vapor	c_w	1864,4	J/(kg·°C)
specific thermal capacity of air	c_a	1005	J/(kg·°C)
coefficient of water vapors diffusion in the air	D_w	$2{,}77\cdot10^{-5}$	m^2/s
coefficient of air diffusion in water	D_a	$1{,}9\cdot10^{-9}$	m^2/s
Henry constant for air diffusion in water	Γ_a	$3{,}82\cdot10^{9}$	$(Pa\cdot m^3)/kg$
heat of phase water-ice transition	r_{w-i}	335000	J/kg
temperature of phase water-ice transition	t_{w-i}	0	°C
ice density	ρ_i	900	kg/m^3
thermal conductivity of ice	λ_i	2,21	W/(m·°C)
thermal capacity of ice	c_i	2140	J/(kg·°C)

5. Results of research into the influence of harmonic pressure oscillations on thermodynamic processes in gas medium of a bubble

Theoretical research. Calculations of oscillation of air bubbles of different dimensions in water were performed according to the proposed mathematical model (1)–(14). Water temperature was accepted as 10 °C at atmospheric pressure. The amplitude of sound oscillation pressure was accepted as 5 kPa for matching the field test. Results of mathematical modelling of parameters of bubbles of different dimensions are shown in Fig. 1–4.

Fig. 1 shows that every size of a bubble corresponds to its resonance frequency, which depends on thermodynamic parameters of gas-vapor mixture inside a bubble and surrounding layers of fluid.

For the assigned resonance conditions, the frequency of bubbles can be determined from the approximation formula, Hz

$$f_R = \frac{5{,}465}{d}, \tag{15}$$

where d is the diameter of a bubble, m.

After the bubbles enter the resonance, the amplitude of oscillation is stabilized at the level of 30–50 % of the radius. This is due to alignment of energy balance: the number of fed energy of sound vibrations is equal energy losses to friction in water, heat and mass exchange near the surface of a bubble.

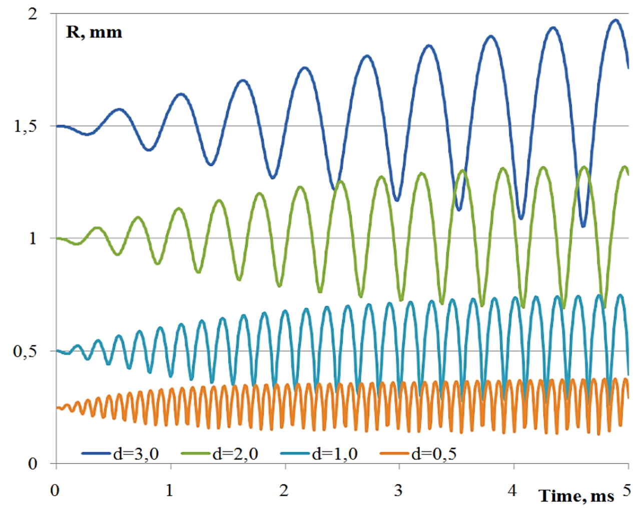

Fig. 1. Change of the radius of bubbles (R, mm) of various dimensions (d, mm) under resonance conditions

Analysis of motion velocity of the walls of a bubble (Fig. 2) shows that it may exceed 6 m/s. This is about a thousand times as much as velocity of a wall during damping oscillations of a bubble. Higher velocities are observed only in cavitation bubbles in the period of maximum compression.

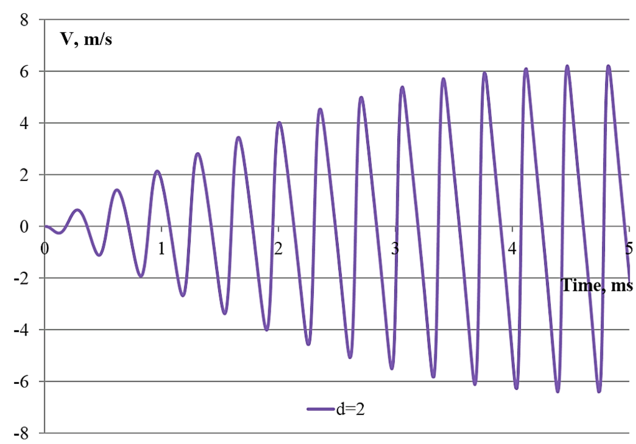

Fig. 2. Rate of change in the radius of a bubble (diameter d=2 mm)

At the same time, there is a change of internal pressure in the anti-phase to the motion of the wall of a bubble (Fig. 3). Calculations show that in half-periods of compression, the inner pressure of a bubble may exceed the ambient pressure as much as by three times. In half-periods of expansion, pressure of the gas-vapor medium decreases compared to ambient pressure of by more than two times. Such pressure fluctuations create preconditions for intensification of heat and mass exchange near the surface of a bubble.

Fig. 4 shows the temperature mode of the gas-vapor medium of a resonance bubble. Temperature fluctuations occur within +13÷–7 °C relative to the initial value. Fluctuations in temperature on the surface of a bubble are shown in Fig. 5. In spite of the simultaneous nature of the fluctuations of gas temperature in a bubble, the temperature mode of water surface differs significantly. The temperature increases by 7.4 °C and decreases only by 1 °C relative to the initial value.

Fig. 6 shows that despite considerable initial amplitude, fluctuations of fluid temperature almost fade after reaching layer 7 (about 7 micron from the surface). The obvious reason for this is a high frequency of oscillations.

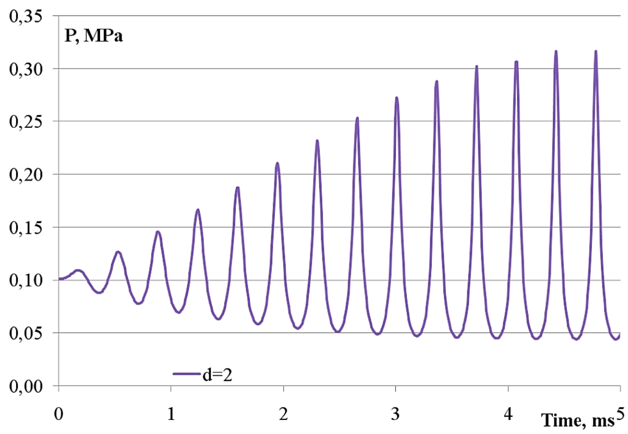

Fig. 3. Diagram of gas pressure in a resonance bubble (diameter *d*=2,0 mm)

A number of calculations, the results of which are shown in Fig. 7, were carried out to analyze the influence of the gas-vapor medium on the amplitude and resonance frequency oscillations. The absence of harmonics at changing the temperature indicates independence of resonance frequency on the temperature of a bubble. A decrease in the amplitude of oscillations at an increase in temperature of gas-vapor medium is an evident fact. The reason for this is intensification of mass transfer processes both near the surface of a bubble and in its gas-vapor medium at an increase in temperature.

Paper [20] presents formula for the calculation of resonance frequency of gas bubbles in fluid, which is widely used in later works of various authors, Hz

$$\omega_o = \frac{\sqrt{3\gamma P_o}}{R\sqrt{\rho_o}}, \tag{16}$$

where R is the radius of a bubble, m; γ is the indicator of the gas adiabat; P_O is the pressure in a bubble in the state of equilibrium, Pa; ρ_O is the fluid density, kg/m^3. This formula is derived under conditions of adiabatic mode of gas, absence of mass exchange and phase transition processes in a bubble, non-viscous fluid and neglecting the forces of surface tension.

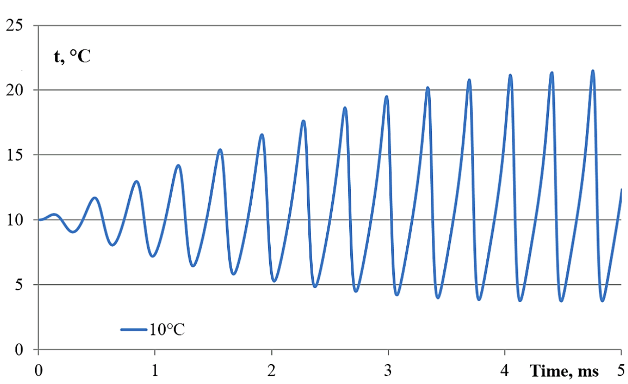

Fig. 4. Diagram of gas temperature in a resonance bubble

For comparison, we will perform calculation of resonance frequency for an air bubble in water under conditions of atmospheric pressure. In the temperature range of 0÷+50 °C, the indicator of air adiabat γ=1.4, gas pressure in the state of equilibrium is 101,325 Pa, the radius of a bubble is 0.001 m, water density is about 1,000 kg/m^3. According to formula (16), resonance frequency for such bubbles, Hz

$$\omega_o = \frac{\sqrt{3\gamma P_o}}{R\sqrt{\rho_o}} = \frac{\sqrt{3\cdot 1{,}4\cdot 101325}}{0{,}001\sqrt{1000}} = 20629.$$

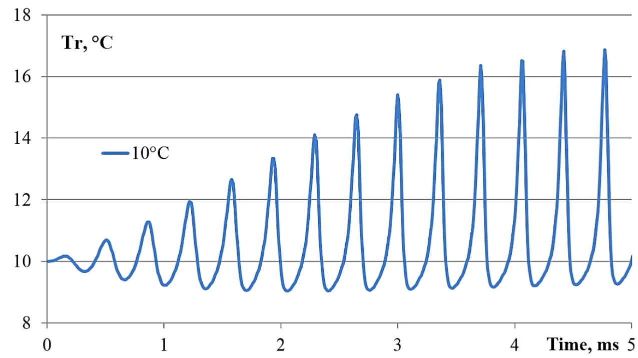

Fig. 5. Temperature of the surface of a resonance air bubble in water

Using formula (15), we will obtain resonance frequency of 2,733 Hz, which is almost 8 times less. The following data of the field test suggest that formula (15) yields more accurate results.

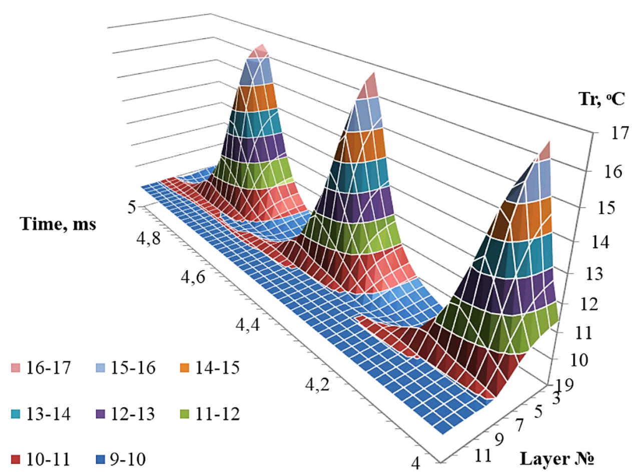

Fig. 6. Temperature of water layers around a resonance bubble

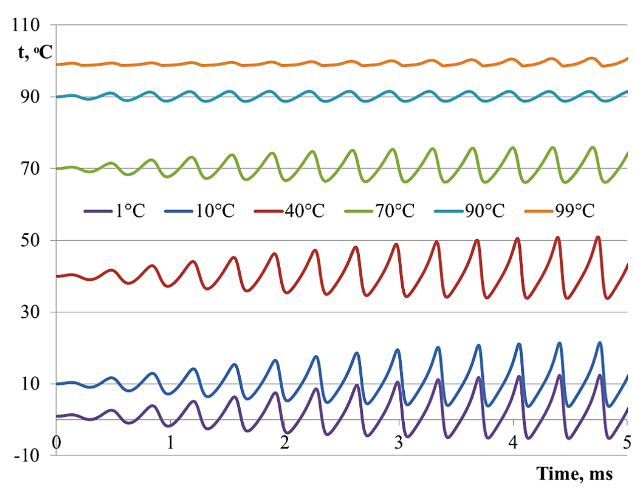

Fig. 7. Influence of fluid temperature on amplitude of resonance oscillations of temperature of gas-vapor medium of a bubble

It is important to analyze the chronological order (Fig. 8) to understand the processes, taking place in an oscillating bubble. For this purpose, we will follow the deployment of various processes in time, which will be divided into 5 stages.

Stage 1. Let us start with the maximum dimensions of a bubble. The pressure in a bubble is minimal. Temperatures of gas and water are approximately equal to each other, so there is practically no heat exchange. There is no condensed water vapor inside a bubble. As a result of the great difference of partial pressures of water vapor near the surface of a bubble and the gas-vapor medium, specific mass flow of water vapor near the surface of a bubble is almost maximum and directed inside a bubble.

Low gas pressure initiates the process of compression of a bubble, a gradual increase in pressure begins. We observe an increase in the temperature of the gas medium and the surface of a bubble. Diffusion of water vapor from the surface of a bubble to the gas medium gradually decreases and reaches zero, when gas pressure becomes equal to atmospheric.

Stage 2. The pressure inside a bubble becomes excessive, the diameter of a bubble decreases and the temperature of its gas-vapor medium increases. Diffusion of water vapor from the gas medium to the wall of a bubble increases. The temperature of water on the surface of a bubble increases. The temperature of the gas-vapor medium of a bubble reaches its maximum. The temperature peak is ahead of the pressure peak of a bubble due to intense heat exchange near its surface.

Stage 3. As a result of an increase in internal pressure, a bubble's compression begins to slow down, and the temperature of its gas-vapor medium starts to decrease. At this time, the temperature on the surface of a bubble reaches a maximum. The mass flow of diffusing water vapor to the wall of a bubble continues to grow and reaches a maximum at the moment of maximum pressure inside a bubble. The dimensions of a bubble at this moment are minimal.

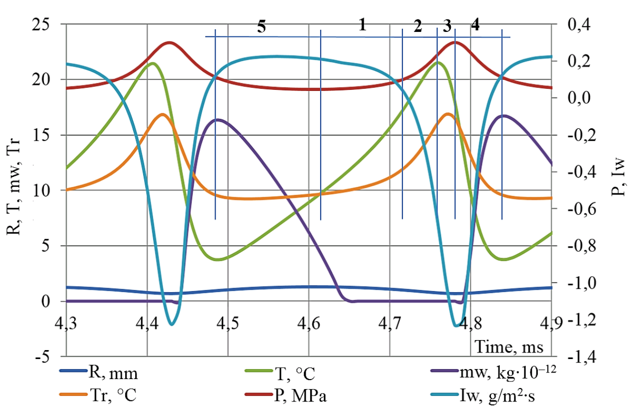

Fig. 8. Chronology of thermo-physical processes of a resonance bubble

Stage 4. The dimensions of a bubble increase, while pressure and temperature decrease. Due to a rapid decrease in gas temperature and a pressure decrease in a bubble, condensation of water vapor in the volume of a bubble begins and abruptly increases – fog formation occurs. The condensate mass reaches the maximum under conditions of medium pressure and the minimum temperature inside a bubble.

At low temperatures, condensation of water vapor inside a bubble almost does not influence the temperature mode, since the mass of condensed water vapor is negligible. When approaching the water boiling temperature, condensation and evaporation of water vapor in the volume of a bubble begins to play a key role in an increase in the amplitude of oscillations.

Stage 5. During subsequent extension of a bubble, gas pressure decreases to the level that is below atmospheric. Due to intense heat exchange from the surface, gas is heated inside a bubble. At the same time, condensation (fog) gradually evaporates. Evaporation of water vapor from the surface of a bubble reaches its maximum and then begins to decrease gradually. Stage 5 ends when a bubble reaches the maximum dimensions.

After that the whole cycle of thermodynamic processes repeats.

Field tests. A research setup was assembled for the field tests of resonance processes in bubbles (Fig. 9). Harmonic oscillations in the water were created using piezoceramic resonator with the diameter of 27 mm. It was powered by the multi-vibrator of alternating frequency with an amplifying output cascade. In general, the multi-vibrator covers the frequency range from 280 Hz to 500 kHz. In the experiments, the frequency of the output signal was determined by the electronic frequency meter F 5311, and the shape was determined by the oscilloscope N313.

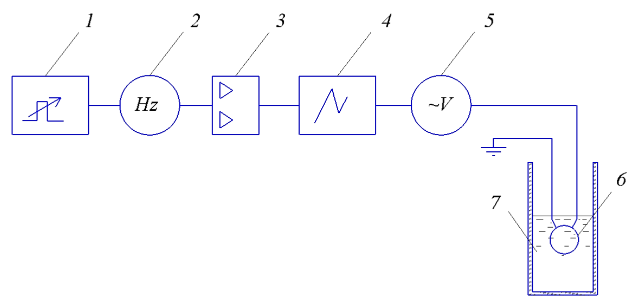

Fig. 9. Schematic of the setup for studying bubbles in resonance acoustic field: 1 – master multi-vibrator; 2 – frequency meter; 3 – two-stroke amplifier; 4 – oscilloscope; 5 – voltmeter; 6 – piezoceramic resonator; 7 – fluid

By the experimental data, the power, connected to the emitter in the frequency range of 2÷5 kHz, was approximately 0.6 W. With regard to the area of the resonator surface, its specific power is 1,047 W/m^2, which corresponds to sound pressure in water of P=5,404 kPa (Fig. 10). This sound pressure is equivalent to the sound volume of 168.6 dB. "Blockage" of the characteristics of the resonator, the cause of which is operation of the emitter destruction protective system, was observed at frequencies of above 100 kHz.

Water was fed to the capacity under pressure in order to obtain bubbles. In case there are bubbles of resonance dimensions in the water, according to formula (15), oscillations begin to be observed and overall sound increases by ten times. The fragment of a sound track recording during a bubble entering resonance is shown in Fig. 11. In comparison with the calculation data, the time of an actual bubble entering resonance is 4–5 times as much.

According to the results of field tests, bubbles in clean water at resonance frequencies are quickly divided into a large number of small ones. Moreover, small bubbles are kept inside a large one (a multi-bubble) using the forces of surface tension.

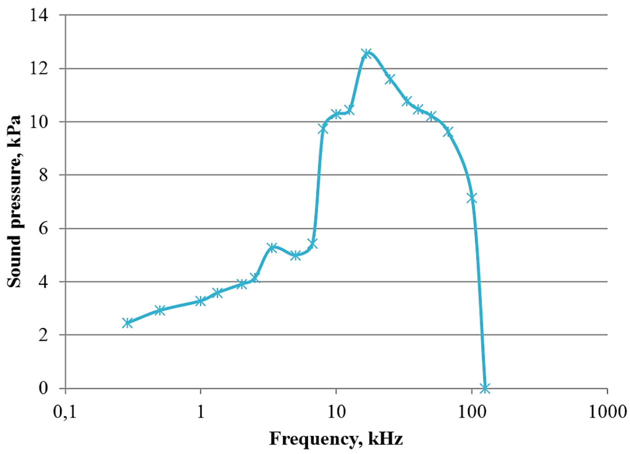

Fig. 10. Sound pressure, created by a piezoceramic resonator in water

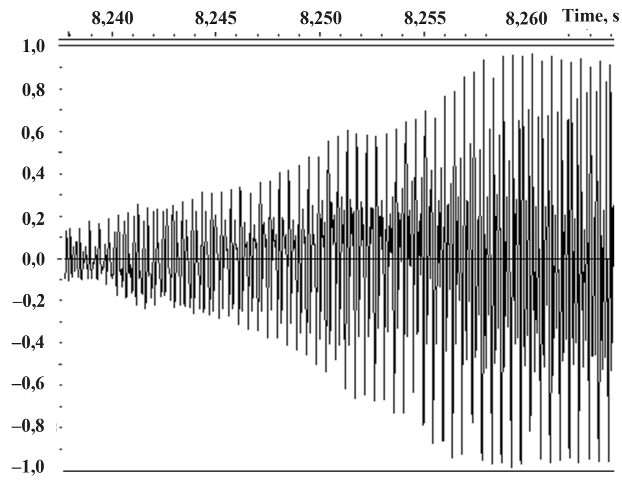

Fig. 11. Fragment of sound track recording during a bubble entering resonance

In distilled water, multi-bubbles begin to be formed at frequency of above 2 kHz and cease to be formed at frequencies of above 3 kHz. Maximum activity is observed at 2.5 kHz, which corresponds to the diameter of bubbles of 2.3 mm. Upon reaching the maximum size (3.6–4.1 mm), a multi-bubble can be divided into smaller ones (Fig. 12) or can explode with formation of a cloud of small bubbles. In other cases, a large bubble can be a source of small ones, which constantly “break away” from a large one and start an “independent” life in fluid.

Addition of surfactants (SAS) to water immediately extends the range of formation of multi-bubbles. These structures begin to appear at frequency of 830 Hz and finish their formation at frequencies above 5 kHz. The most active formation of multi-bubbles is observed at frequency of 2.5 kHz. When using SAS, the number of small bubbles in a large one increases significantly. An “explosion” of such multi-bubble with formation of a cloud of microscopic bubbles is seen in the video images, Fig. 13.

In general, experimental studies proved existence of resonance of gas bubbles in water at calculation frequencies. In addition, it was possible to obtain multi-bubbles and a large number of bubbles of dimensions less than 0.1 mm.

a *b* *c*

Fig. 12. Division of a large multi-bubble into two ones of smaller dimensions (video images left-to-right): *a* – initial moment; *b* – in 0.03 s; *c* – in 0.06 s

a *b* *c*

Fig. 13. Explosion (burst) of a multi-bubble with formation of small bubbles (video images left-to-right): *a* – initial moment; *b* – after 0.03 s; *c* – after 0.06 s

6. Discussion of results of research into resonance oscillations of gas-vapor bubbles

Theoretical and experimental studies of resonance oscillations of gas-vapor bubbles in water is a continuation of a series of papers [17], devoted to thermodynamic processes at the fluid-gas boundary. The obtained results are caused by taking into account heat and mass exchange that occur on the surface and inside an oscillating gas-vapor bubble. The merit of this study is a good match of calculation data with the results of the field test, which was achieved thanks to the improvement of the mathematical model and compliance of the output data of mathematical modeling with the conditions of the field test.

The results of field tests not only proved the theoretically calculated resonance frequencies, but also made it possible to identify an interesting phenomenon of formation of multi-bubbles. When oscillations reach certain amplitude, a large bubble is divided into a very large number of small ones, which are retained inside a large bubble by the forces of surface tension. The obvious consequence of formation of such a structure is a sharp increase in heat and mass exchange surface at the boundary of the contact of phases. However, it is necessary to conduct more detailed studies to refine the quantitative thermodynamic indicators of multi-bubbles.

Calculations and field tests were conducted for bubbles in water under conditions of atmospheric pressure. Development of such research could be analysis of the influence of pressure on resonance characteristics of bubbles, experimental evaluation of mass transfer processes on the inter-phase surface, check of formation of multi-bubbles in other fluids and many others.

There are a few problems that we have to deal with when carrying out experimental research into resonance of bubbles. Above all, this is a limitation of the power of a piezo resonator, an overshoot of which leads to its destruction. In the operating mode, the voltage on the resonator reaches

80 volts, so it is important to provide it with reliable electrical insulation which can withstand mechanical vibrations for a long time.

The results of the conducted studies can have a wide range of applications in various industrial processes, based on heat and mass exchange at the boundary of the gas-fluid contact. The consequence of the use of resonant sound oscillations for bubbling plants, aeration, vacuum distillation, absorption and others may be a decreasing power capacity and increasing rate of technological processes.

7. Conclusions

1. The mathematical model of thermodynamic processes was improved in order to increase the accuracy of calculation of oscillating gas-vapor bubbles under resonance conditions. The model was supplemented by the components that allow taking into account phase transition processes on the surface of a bubble and in its gas-vapor medium, as well as the thermal effects during gas dissolution.

2. As a result of mathematical modeling, the possibility of resonance in gas-vapor bubbles in water in the frequency range of 0.5–5 kHz was established. Quantitative indicators of thermodynamic parameters of a bubble under conditions of resonance were determined. Thus, at the initial temperature of 10 °C and atmospheric pressure for a bubble with diameter of 1 mm, a change in pressure occurs within 0.5–3.0 MPa, a temperature change in gas-vapor medium occurs from +4 °C to +22 °C and the temperature of the surface of a bubble varies within +9–+17 °C.

3. Performed calculations showed that temperature of gas-vapor medium of a bubble does not affect its resonance frequency, however, has a significant impact on the amplitude of oscillations. When fluid temperature approaches its boiling temperature, an abrupt increase in amplitude of oscillations of a bubble occurs. For example, amplitude of oscillations of the wall of a bubble decreases by six times at an increase in water temperature from +10 °C to +99 °C.

4. The existence of resonance bubbles on calculated frequencies was experimentally proved. The field observations showed that resonance oscillations of bubbles are accompanied by formation, growth and destruction of multi-bubbles. Long-term effect of sound waves at resonance frequencies leads to formation of a very large number of bubbles of dimensions of less than 0.1 mm in fluid volume. It was established experimentally that application of SAS considerably expands the frequency range of formation of multi-bubbles and increases the number of small bubbles inside a large one. This makes it possible to increase the area of heat exchange and mass exchange surface of bubbles.

Application of the resonance of bubbles has great prospects for intensification of many technological processes, based on heat and mass exchange processes at the fluid-gas boundary.

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ANALYSIS OF THE EFFECT OF ULTRAVIOLET IRRADIATION ON VARROA MITE

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Представлені результати аналітичних досліджень впливу електромагнітних опромінювань оптичного спектру на біооб'єкти в УФ діапазоні (UVB, UVC). Отримані математичні вирази моделювання конструктивних характеристик захисних пристроїв від варроатозу. Запропоновано пристрій (льоткова приставка), який забезпечений світлодіодними модулями УФ випромінювання, що живляться від сонячних фотоелементів

Ключові слова: ультрафіолетове випромінювання, довжина хвилі, доза опромінення, кліщ Варроа, боротьба з варроатозом

Представлены результаты аналитических исследований воздействия электромагнитных излучений оптического спектра на биообъекты в УФ диапазоне (UVB, UVC). Получены математические зависимости моделирования конструктивных характеристик защитных устройств от варроатоза. Предложено устройство (летковая приставка), обеспеченное светодиодными модулями УФ излучения, питающимися от солнечных фотоэлементов

Ключевые слова: ультрафиолетовое излучение, длина волны, доза облучения, клещ Варроа, борьба с варроатозом

1. Introduction

An efficiency increase in the field of beekeeping is impossible without development and implementation of progressive resource-saving technologies and means of their implementation aimed at ensuring proper veterinary and sanitary conditions for maintenance, breeding and use of bee colonies. This fully applies to the development of means for prevention and treatment of bee diseases in active and passive periods of their life. Creation of the new beekeeping implements, which are capable of meeting the requirements of biosafety technologies, is an urgent problem for the design of technical means to control bee varroatosis with a use of UV irradiation. A promising development in mentioned area is creation of unified protective devices located outside nursing sockets. The devices are hive entrance attachment equipped with a module of UV radiation capable of performing several preventive and therapeutic functions simultaneously. In particular, it is formation of conditions for reduction of non-technological losses of the biopotential of a bee colony, preservation of its feeding stocks and possession of highly specialized characteristics, which ensure the reliable operation of a hive entrance attachment in the struggle with bee varroatosis [1, 2].

2. Literature review and problem statement

Varroatosis is an invasive disease of bee colonies, which causes significant material damage in the field of beekeeping and plant growing. It affects a level of food security of a country negatively. There are several types of known technologies to struggle with the disease: chemical, zootechnical, physical and combined. The aim of them all is inhibition or