Generation of High-Dispersed Liquid-Drop Systems in the High-Intensity Ultrasonic Fields

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Abstract: - The paper is devoted to theoretical studies of process of two-stage high-dispersed dispersing of liquids. The process includes primary formation of large drops by ultrasonic influence on thin liquid film and second breakup of obtained drop under high frequency acoustic field influence in dispersed medium. The physical mechanism and physical and mathematical model of secondary drop breakup under high frequency acoustic field in dispersed medium were proposed. The model allowed to determine threshold oscillations energy at different drop sizes, properties of dispersed liquid and influence types. It is derived, that most effective method of acoustic influence is radiation of different frequency pulses at high concentration of dispersed phase (more 10 % vol.) providing conditions of intermodal dispersion. The paper shows that continuous one-frequency oscillations the radiator power can be more than 40 kW. The pulsed influence reduces the required radiator (with radiation surface area 800 cm^2) power to 2 kW.

Keywords: Ultrasonic, aerosol, high-dispersed liquid, pulsed influence, wave packets

1. INTRODUCTION

The application of heterogeneous systems with high-dispersed liquid phase is the effective and promising trend of accommodation disinfection, neutralization of dangerous aerosols, increase of power factors of existing types of fuel and production of new ones, drying of various materials, etc. It is caused [1-4] by specifically large mass of phase boundary in comparison with the systems having film or foam structure. It is known, that dispersion of even 2 ml of disinfecting aerosol containing 0.16% of polyhexamethyleneguanidine hydrochloride and didecyldimethylammonium chloride (0.03%) (“Aeron”) provides disinfection of 1 m^3 of air. Another example, the dispersion of even 1% of water [3] in hydrocarbon fuel (petrol, diesel oil, furnace fuel oil, etc.) increases efficiency of the internal combustion engines and the sprayer burners in more than 5% (if the size of the emulsion drops is 2…3 microns).

At present the generation of high-dispersed liquid phase based on the entering of low-frequency ultrasonic vibrations (at the frequencies of 22…250 kHz) in the layer, which borders with the carrying media, is the most efficient method. It allows realizing liquid dispersion both in gas carrying medium (spraying) and in another liquid (emulsification).

The ultrasonic dispersion has following advantages:

– there is no necessity to use auxiliary substances (emulsifiers, surface-active substances or spraying agents);

– the possibility of dispersion of high-viscous liquids;

– small size variation of formed drops relative to the mean value;

– high efficiency of the process.

The large number of the publications devoted to the determination of the dependences of the dispersed features of the formed drops both in liquid (emulsion) and gaseous phases (aerosol) on the modes of the ultrasonic action proves prospects of appointed method of liquid dispersed drop generation. The examples of the dependences obtained experimentally or theoretically are given in the publications of research groups of Nagoya University [5] (Japan), Harvey Mudd College [6] (California, USA) and University of Salerno [7] (Italy), Asami T. (Japan) [8], Altai State Technical University named after I.I. Polzunov [9-12] (Russian Federation) – for spraying; Omsk State Technical University [13] (Russian Federation), École nationale supérieure de techniques avancées [14] (France), Chulalongkorn University [15] (Thailand), Okayama University [16] (Japan), HielscherGmbh. [17] (Germany), Institute of Chemistry [18] (Poland) – for emulsification.

Unfortunately, in spite of mentioned above advantages and great interest of the researchers [1-3, 5-18] at present there is a problem to provide high productivity at the formation of the drops with the size of less than 10 micron. It is caused by the fact that the productivity according to the theoretical and experimental results obtained before [5-18] is in inverse proportion to the size of the drops and it is insufficient at the formation of high-dispersed drops.

At present maximum achieved productivity of the drop generation with the size of 60…100 micron is 1 ton per hour due to the application of the ultrasonic radiators with enlarged surface area (up to 800 cm^2) [19, 20], and for the drops with the size of less than 10 micron it is no more than 4 l per hour.

Thus, it is an actual task to find new approaches to the formation of high-dispersed liquid phase with increased productivity in the ultrasonic fields.

2. PROPOSED METHOD OF HIGH-DISPERSED LIQUID PHASE FORMATION IN THE ULTRASONIC FIELDS

Insufficient productivity of the ultrasonic dispersion at the formation of high-dispersed drops first of all is caused by the fact that the dispersion consists of one stage, at which the drop tears away from the layer interface of the liquid phase and the carrying medium.

At the application of all known approaches the vibration frequency of up to 5 MHz is required for the formation high-dispersed liquid drops [5-12]. However high-frequency vibrations limit the area of the radiating surface, quickly attenuate in the dispersed liquid and they are highly absorbed by the material of the ultrasonic radiator. Thus, it is impossible to provide high efficiency of the dispersion at high dispersity with the help of the ultrasonic action in the frames of one stage.

That is why it is proposed multi-stage method of the ultrasonic dispersion of liquids. According to it at the first stage from the layer interface of dispersed liquid and carrying medium large drops are generated under the action of low-frequency ultrasonic vibrations (20…30 kHz). The diameter of generated drops is determined by the profile of the capillary waves formed on the surface of liquid layer under the action of cavitation produced by low-frequency ultrasonic action. The influence of the modes of ultrasonic action on the profile of the capillary waves and as a sequence on the drop diameter was totally studied in the papers of Lang R. J., Boguslavskiy U., Eknadiosyants O.K. [21, 22]. The authors obtained following expression for the drop diameter formed from the surface of liquid layer and the dispersion productivity according to liquid mass separated from the surface unit in the time unit:

$$D_1 = 0{,}34\lambda = 0{,}34\sqrt[3]{\frac{8\pi\sigma}{\rho f^2}}\,. \qquad (1)$$

$$\Pi_1 = 2\frac{f}{\lambda^2}\pi\frac{D_1^3}{6} \qquad (2)$$

where λ is the length of the capillary wave, m; f is the frequency of the ultrasonic vibrations, Hz; σ is the surface tension of the dispersed liquid at the interface with gas phase or another liquid, N/m; ρ is the liquid density, kg/m^3; D_1 is the drop diameter, m; Π_1 is the specific productivity of dispersion, m^3/(m·s).

The disperse phase generated at the first stage and suspended in the carrying medium is acted upon by the action of the ultrasonic field from the side of the carrying medium. Due to it the drops are deformed and broken and the drop powder evolves further. The process repeats for each of formed drops many times, as it is shown in Figure 1.

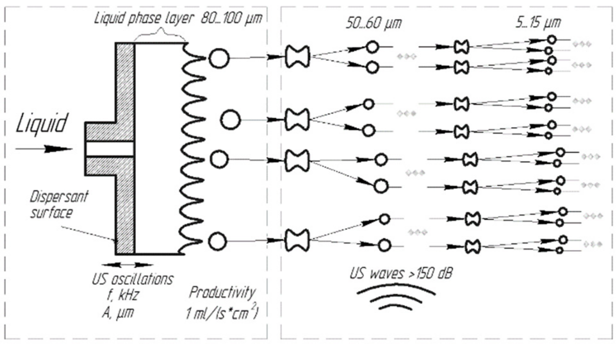


Figure 1. Method of highly productive multi-stage formation of high-dispersed drops in the ultrasonic fields

At the stage of the drop deformation under the action of carrying medium flow the wall of the drop changes form symmetrically about the axis, which direction is congruent to the direction of ultrasonic vibrations. The symmetry of the drop deformation is concerned with initial sphericity of the drop and the assumption of plane wave, at which the flow of the carrying medium is considered to be cylindrically symmetric.

The change of the drop form is caused by the generation of the capillary waves on its surface. The formation of the capillary waves on the interface of gas and liquid or two immiscible liquids is studied well in the papers of J.W. Stratt (Lord Rayleigh), U.Y. Boguslavskiy, O.K. Eknadiosyants and others and it is aroused by the interchange of maximums and minimums of surface tension forces because of the mass conservation law. The difference of the forces between neighboring points of the maximum and the minimum of the surface tension leads to the flow of liquid from the zone of the highest surface curvature to the zone of the lowest curvature. As a result of it maximums and minimums of the surface tension forces change their places. Further the process repeats periodically.

In the flow of vibrating carrying medium the capillary waves on surface of drop occurs due to the difference of surface forces from the side of the carrying medium acting upon the central 1 and peripheral 2 areas (Figure 2). This difference is caused by the fact, that the vector of vibrating speed of carrying medium flow **u** has different angles with the normal vectors of the surface of these areas.

Vibrating frequency of the capillary waves is congruent to the excitation frequency, i.e. with the vibrating frequency of the carrying medium.

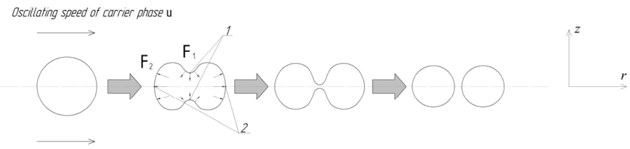


Figure 2. Scheme of the deformation and the breaking of the drop in the ultrasonic field

As a drop initially has a spherical form, the disturbance of the drop walls has a character of radial capillary waves with the profile $R(\theta)$, where R is the length of the vector radius **r** of the drop wall point, equals to $\sqrt{r^2 + z^2}$, $\theta$is the polar angle between the radius-vector **r** and the axis z.

If the angles are θ=0; θ=π considering symmetry of the drop deformation the conditions $\frac{\partial R}{\partial \theta} = 0$ are valid; similar to the conditions of the wave reflection. That is why radial capillary waves on the drop surface are standing.

According to this, number of half waves in the drop circle must be natural. According to the earlier studies [23], the wave, length of which equals half length of the drop circle, has the highest amplitude.

Thus, as a result of the deformation the drop gets the form of “dumb-bell”. When the value of the drop deformation $\max\limits_{\theta \notin [0;\pi]} \left| R(\theta) - \frac{D}{2} \right|$ exceeds critical value, equals to

$$\max_{\theta \notin [0;\pi]} \left| R(\theta) - \frac{D}{2} \right| \geq \frac{D}{4}, \quad (3)$$

where D is the diameter of the initial drop, m; at the central part of the “dumb-bell” (see Figure 2) further avalanche-like decreasing of its thickness begins. Next stage of the drop breaking comes.

As the length of the capillary wave on the surface of the drop is congruent to half length of the drop circle, as a result of the breaking of one drop with the diameter D two equal drops with the diameter of $\frac{D}{\sqrt[3]{2}}$ are formed.

Then for each of two newly generated drops the cycle deformation-breaking repeats.

The advantages of proposed multi-stage method:

– high productivity of generation of high-dispersed drops (less than 10 micron) due to the primary dispersion of large drops (40 – 80 micron). According to the studies [5–17] carried out before the dispersion of large drops is characterized by up to 200 times more productivity in comparison with the small ones. Breakup of large drops into small ones takes no more than several tens of the ultrasonic vibrations periods (no more than 0.2 s);

– there is no necessity to form high-frequency ultrasonic vibrations (more than 60 kHz) requiring complication of the radiator construction, focusing for providing of vibration energy necessary for the dispersion and highly absorbed in the radiator material and in insonified medium.

To achieve maximum efficiency of proposed multi-stage method it is necessary to determine the features of the ultrasonic action (according to energy and frequency spectrum of formed ultrasonic field) on the base of study of drop deformation and breaking in the vibrating flow of the carrying medium.

Nowadays the formation of the ultrasonic drops in the layer at the 1st stage [9-12] is the most fully studied. While the processes of drop deformation and breaking under the action of the ultrasonic field in the carrying medium are investigated to a lesser degree.

Further proposed model of the drop deformation and breaking under the action of high-intensity ultrasonic fields.

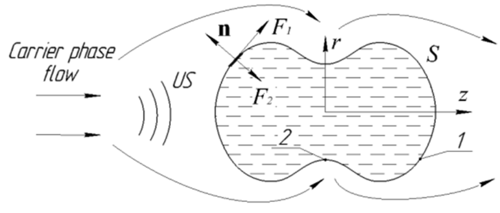
3. PHYSICAL-MATHEMATICAL MODEL OF THE ELEMENTARY ACT OF THE DROP BREAK-UP IN THE HIGH-INTENSITY ULTRASONIC FIELDS

The model is based on the calculation of liquid motion in the volume of the drop under the action of the following forces (Figure 3) [20, 23]:

– dynamic pressure differential in vibrating flow of the carrying medium;

– difference of the surface tension forces at the wave-like disturbances of the drop wall at the various parts of the surface of the last one (**F₂**);

– forces of viscous stress at the motion of the walls with non-nil speed (**F₁**).



n – normal vector to the drop wall; S – drop surface; (r, z) – axes of the cylindrical coordinates

Figure 3.Scheme of the drop deformation in the ultrasonic field

Under the action of mentioned forces, the deformation of the drop surface occurs and at specified energy of the ultrasonic vibrations the stage of the drop breaking comes.

The value of maximum drop deformation $\max\limits_{\theta \notin [0;\pi]} \left| R(\theta) - \frac{D}{2} \right|$ is in proportion to vibration energy. As the drop breaking begins, when maximum deformation exceeds a quarter of the drop diameter $D/4$, there is threshold vibration energy, which is necessary for breaking of the separate drop.

To determine threshold vibration energy we calculate the drop deformation by numerical method of lattice Boltzmann equations [24] based on liquid flow inside each drop as a motion of ensemble of pseudoparticles having certain function of the discrete velocities distribution $N_k(\mathbf{x},t)$. $N_k(\mathbf{x},t)d\mathbf{x}$ is the number of the pseudoparticles having speed $\mathbf{c}_k$ and being in the volume $d\mathbf{x}$. The speeds $\mathbf{c}_k$ are chosen in a following way, that in the step of time Δt the particles move to the neighbor points of the space lattice, which vectors satisfy condition $\mathbf{r}_k = \mathbf{c}_k \Delta t$.

The concentration of liquid pseudoparticles in the drop in every step of time is calculated according to the following expression:

$$N_k \begin{pmatrix} (r + c_{kr}\Delta t)\cos\theta, (r + c_{kr}\Delta t)\sin\theta, z + \\ + c_{kz}\Delta t, t + \Delta t \end{pmatrix} = \\ = N_k(r\cos\theta, r\sin\theta, z, t) + \Omega(N) + \Delta N_k , \quad (4)$$

where Ω_k is the collision operator; ΔN_k is the change of the particles concentration due to the action of bulk forces, m^{-3}; $(r; z)$ are the coordinates of the surface point of deformed drop depending on the angle θ between the radius-vector of the point and the axis z, m.

From the side of carrying medium flow it is set boundary condition of harmonic disturbances at infinity (at large distances from the drop):

$$u(t) = u_0 \sin(\omega t) = \sqrt{\frac{2e}{\rho}} \sin(\omega t); \quad (5)$$

where ω is the vibration frequency of the carrying medium, s^{-1}; u_0 is the amplitude of the vibrating speed of the carrying medium, m/s; e is the energy of the ultrasonic field (the ratio of vibration intensity to the speed of sound in the carrying medium $e = \frac{I}{c}$), J/m^3; u is the flow speed component of the carrying medium along the axis z at large distances from the drop, m/s.

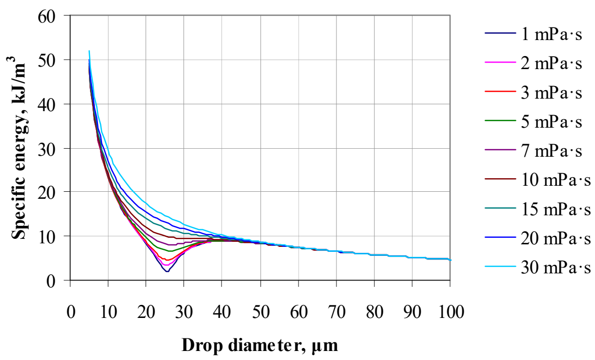
The calculation of the evolution of pseudoparticle concentration in liquid allows determining the value of maximum drop deformation:

$$x = \max_{\theta \in [0;\pi]} \sqrt{\left(\frac{d}{2}\sin\theta - r(\theta)\right)^2 + \left(\frac{d}{2}\cos\theta - z(\theta)\right)^2},$$

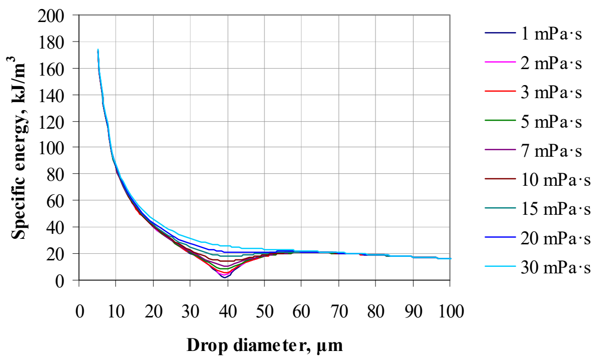
where d is the initial diameter of the drop, m; $[r(\theta); z(\theta)]$ are the coordinates of the points of the drop wall, which are located at the interface "continuous liquid-saturated vapor of liquid" [24].

Maximum deformation determines the possibility of drop breakup. The criterion of the drop breakup is $x > D/4$, when Weber number exceeds critical value $We > We_{cr.} = 6$ (the surface tension force in the central area of the drop 2 exceeds the surface tension forces in the peripheral areas 1 (see Figure 2) because of the local thinning of the drop) [23].

Further calculated dependences of the minimum energy of the ultrasonic field, which is necessary for the realization of the elementary act of the drop breaking under the action of sinusoidal vibrations of one frequency (Figures 4, 5) are given.

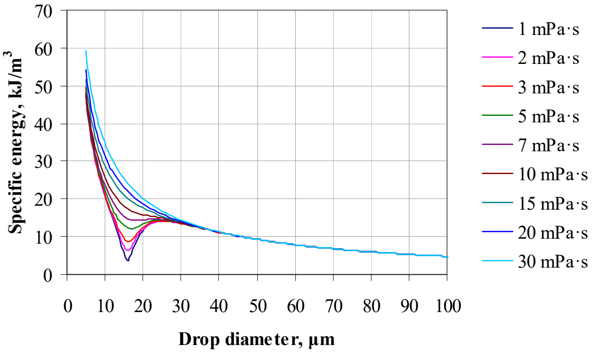


a) 20 mN/m

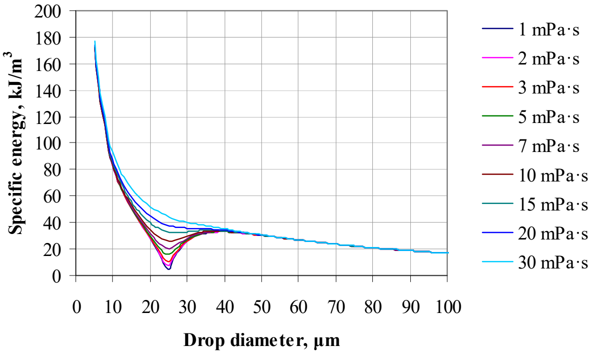


b) 72 mN/m

Figure 4. Dependences of the ultrasonic field energy on the drop diameter at different viscosities and surface tensions of the liquid (the frequency is 22 kHz)



a) 20 mN/m



b) 72 mN/m

Figure 5. Dependences of the ultrasonic field energy on the drop diameter at different viscosities and surface tensions of the liquid (the frequency is 44 kHz)

From the obtained dependences it follows, that there are some drop diameters, at which vibration energy necessary for the drop breaking achieves local minimum (less than 10 kJ/m^3). They are the resonance diameters at the specified properties of liquids. However, in practice it is not possible to act continuously at the frequency corresponding to the resonance diameter of the drops, as the drop diameter changes uninterruptedly due to breaking and evaporation. Herewith the ultrasonic radiator is able to generate maximum level of acoustic pressure only at final frequency set, which are caused by the resonance properties of the radiator.

That is why vibration energy generated by the radiator should be in 20…160 kJ/m^3 higher than it is necessary for the breaking of the drops of the resonance diameters. Moreover, the viscosity growth leads to smoothing of resonance minimums of the threshold level of the ultrasonic field energy, but it influences weakly upon the value of the resonance diameter. Minimums of vibration energy totally disappear beginning with the viscosity of 30 mPa·s.

In whole for the dispersion of liquid phase the characteristics of the ultrasonic field should satisfy following requirements:

1) specific energy of generated field should be more than 20 kJ/m^3;

2) generated ultrasonic field should exclude the appearance of cavitation in the dispersed liquid and the carrying medium, if it is in liquid aggregate state. It is because the appearance of cavitation essentially reduces a part of vibration energy spent on the conversion of liquid into dispersed state.

However, following physical limitations prevent the generation of ultrasonic fields with such high energy features:

1) the vibration energy required for the realization of the elementary act of the drop breaking is more than 20 kJ/m^3 for large drops (80 – 100 micron) and more than 80 kJ/m^3 for small drops (5 – 15 micron). At the energy values, in liquid to be dispersed it appears cavitation, which leads of 99% of energy to the heating of liquid due to the local temperature increasing in the nuclei of the cavitation bubbles up to 5000 K [2, 3].

2) at the dispersion in the carrying gas medium this specific power cannot be achieved with the help of existing radiators, as maximum vibration energy generated by the existing sources of ultrasonic action for gaseous and gas-dispersed media does not exceed 1 kJ/m^3. While for the drop breaking the vibration energy of more than 20 kJ/m^3 is required. For the vibration energy, the power of the radiator should be more than 40 kW (if the area of the radiating surface is 0.08 m^2).

Thus, it is determined, that it is impossible to realize multi-stage dispersion at mono-frequency ultrasonic action. That is why it was proposed the method of action by sequence of wave packets of different frequencies providing energy, which is necessary for the drop breaking at low power of the radiator. Proposed method of generation of the ultrasonic field is described in the next part.

4. STUDY OF THE DROP BREAKING AT THE ULTRASONIC ACTION BY THE SEQUENCE OF THE WAVE PACKETS OF DIFFERENT FREQUENCIES

4.1. Generation of high-intensity ultrasonic field under the action of sequence of the wave packets of different frequencies

For the formation of high-intensity ultrasonic field with the characteristics sufficient for the drop dispersion at relatively small power of the radiator it is evident, that it is necessary to concentrate energy in space and/or in time.

It is proposed the method of energy concentration – radiation of sequence of wave packets of finite length (no more than 10 ms) at multiple frequencies (ultrasonic impulses), as it shown in Figure 6. Due to the intermode dispersion caused by the presence of heterogeneous inclusions (liquid drops) in the multiphase medium the wave packets will have different propagation velocity and at some distance from the radiator will make superposition (Figure 6c).

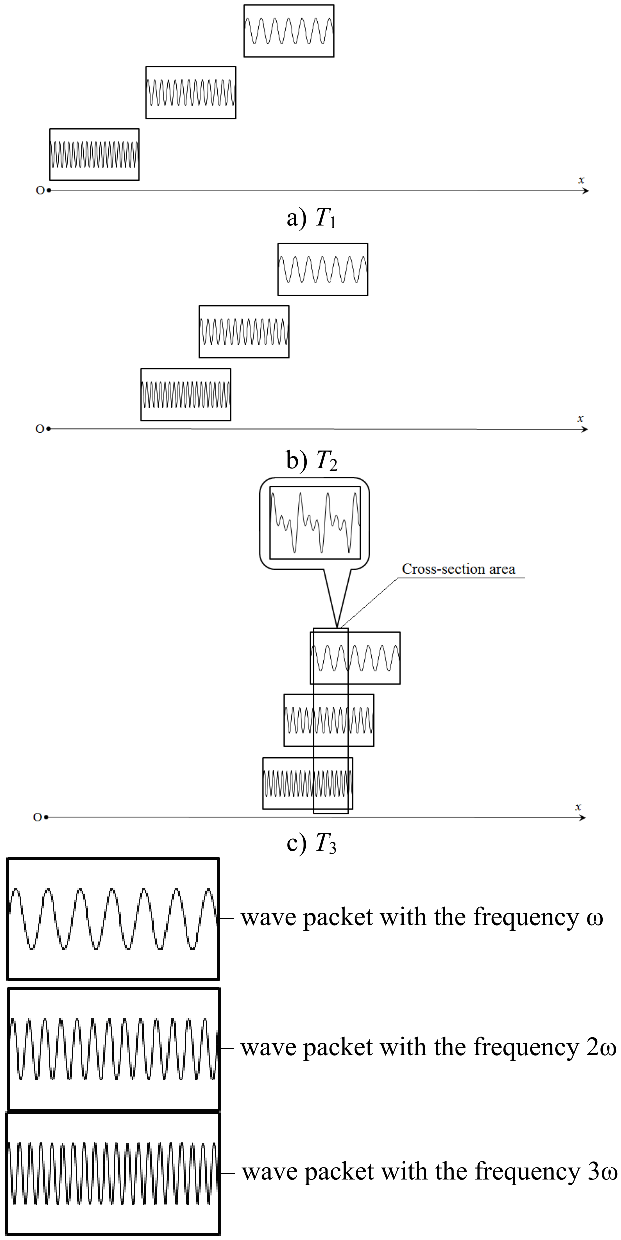


Figure 6. Position of wave packets of different frequencies relative to the radiator (the radiator is in the point *O*) in different instants of time $T_3>T_2>T_1$

According to Figure 6 the wave packets with multiple frequencies ω, 2ω, 3ω, … are radiated consequently at different instants of time. As each wave packet has fixed duration τ and it moves in the medium along the axis x with fixed speed depending on the frequency of the wave packet $c(\omega)$ it occupies finite domain in space with constant extension $l(\omega)=c(\omega)\tau$.

As the wave packets are radiated consequently (in different instants of time), at beginning of their motion (instant of time T_1) they occupy noncrossing domains (Figure 6a). Further due to the difference of propagation speeds ($c(\omega)<c(2\omega)<c(3\omega)<\ldots$) the wave packets begin to "overtake" each other. For instance, in instant of time T_2 (Figure 6b) the wave packet of the frequency ω is crossed with the wave packet of the frequency 2ω, and the wave packet of the frequency 2ω is crossed with the wave packet of the frequency 3ω. Then in the instant of time T_3 (Figure 6c) the wave packets with the frequencies ω, 2ω, 3ω have one similar crossing domain with the extension exceeding $l(\omega)/3$. In this domain the superposition of the wave packets occurs and the vibration amplitude exceeds the vibration amplitude of the single wave packet in more than 2 times. Consequently, the vibration energy increases in up to 3 times.

Proposed method of the ultrasonic field generation has following advantages:

– the possibility of manifold increase of the vibration energy even at the application of low-power radiators;

– the possibility to control the position of the domain, in which the superposition of the wave packets occurs and, consequently, dispersion will be realized;

– the absence of undesirable cavitation phenomena in liquid to be dispersed due to finite duration of impulse [24];

– the possibility to increase vibration amplitude due to the superposition of the wave packets not depending on the geometry of the technological volume and the form of the ultrasonic radiator;

– the absence of coagulation of the particles because of small finite duration of the wave packet (no more than 10 ms), as mean time required for the aggregation of two particles is big in comparison with the duration of the single wave packet and it is more than 0.5 s [25, 26].

To make conditions for the formation of high-intensity ultrasonic field it is necessary to carry out analysis of propagation of the wave packets in the carrying medium taking into account influence of liquid drops. The analysis of propagation of the wave packets is based on the wave equation obtained from general dynamic equations of the heterogeneous media with the dispersed phase in the form of liquid spherical drops [27]:

$$\rho_{10}\frac{\partial\alpha_1}{\partial t}+\frac{\alpha_{10}}{c^2}\frac{\partial p_1}{\partial t}+\rho_{10}\alpha_{10}div\mathbf{v}_1=0;$$

$$\frac{\partial\alpha_2}{\partial t}+\alpha_{20}div\mathbf{v}_2=0;$$

$$\alpha_{10}+\alpha_{20}=1;$$

$$\alpha_1+\alpha_2=0;$$

$$\rho_{10}\alpha_{10}\frac{\partial\mathbf{v}_1}{\partial t}=-\nabla p_1-\frac{9\mu\alpha_{20}}{2a^2}\left(\mathbf{v}_1-\mathbf{v}_2\right);$$

$$\frac{\partial \mathbf{v}_2}{\partial t} = \frac{9\mu(\mathbf{v}_1 - \mathbf{v}_2)}{2\rho_{20}a^2};$$

where ρ_{10} is the density of air, kg/m^3; ρ_{20} is the density of liquid, kg/m^3; α_{10} is the balanced volume air content; α_{20} is the balanced volume liquid content; c is the speed of sound n air; $\mathbf{v}_1$ is the air speed, m/s; $\mathbf{v}_2$ is the speed of liquid, m/s; μ is the air viscosity, Pa·s; a is the radius of liquid drop, m; p_1 is the air pressure, Pa; α_1 is the disturbance of volume air content; α_{20} is the disturbance of volume liquid content.

Obtained wave equation includes non-null right part taking into account influence of liquid drops. The right part is double integral from the prehistory of sound pressure change with exponentially decreasing weighting coefficient:

$$\Delta p_1 - \frac{\alpha_{10}}{c^2}\frac{\partial^2 p_1}{\partial t^2} = = -\frac{9\mu\alpha_{20}}{2a^2}\frac{1}{\tau_2}\int_0^t\left[\int_0^{t_1}\frac{e^{\frac{\alpha_{20}}{\alpha_{10}\tau_2}(t_2-t)}}{\rho_{10}c^2}\frac{\partial^2 p_1}{\partial t^2}\partial t_2\right]\partial t_1, \quad (6)$$

where α_{10} is the balanced volume air content, %; α_{20} is the balanced volume liquid content, %; c is the sound speed in air, m/s; ρ_{10} is the density of air, kg/m^3;
μ is the viscosity of air, Pa·s; a is theradius of liquid drop, m; p_1 is the air pressure, Pa;
τ is the relaxation time, s.

The calculations of sound speed in the carrying medium with dispersed liquid phase carried out on the base of the equation (6) allow determining, that at the volume concentration of the dispersed phase of no less than 10% the sound speed increases in 1.5 time at the rise of frequency from 22 to 66 kHz (Figure 7).

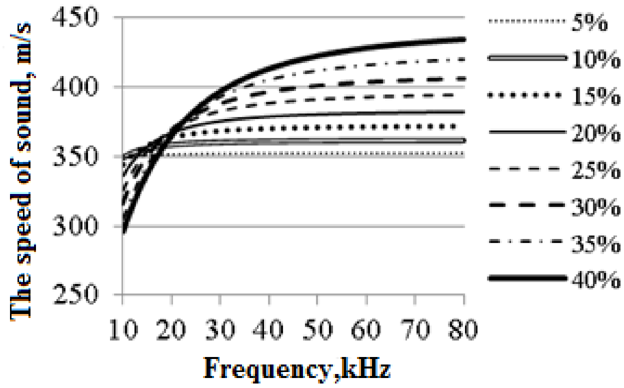


Figure 7. Dependence of sound speed on frequency of the ultrasonic waves at different volume content of the dispersed phase (the drop diameter is 20 micron)

At such difference of sound speeds the wave packets superpose on each another at the distance of no more than 40 cm from the surface of the radiator (Figure 8).

To prove this fact the calculation of propagation of the wave packets of different frequencies in the extensive channel is carried out.

It is calculated by numerical solution of the equation (6) with the help of finite-difference method with the application of spectral decomposition of pressure disturbance p_1.

It is considered propagation both separate monofrequency wave packets of 22 and 44 kHz and superpositions of interchangeable wave packets at their consistent radiation with the interval of 0.3 ms. Calculated distribution of specific energy of the wave packets in the extensive channel of 900 mm in each instant of time is shown in Figure 8.

As it follows from presented distributions, maximum vibration energy under the action of the wave packet of one frequency does not exceed 20 kJ/m^3. Due to the difference of propagation speeds the different frequencies packets, each packet superposes on each another at the distance of 200 mm from radiator surface. Maximum achieved vibration energy achieves 40 kJ/m^3 (the zones marked with red color in Figure 8c).

Thus, it is determined, that it is possible to concentrate ultrasonic energy with the help of proposed method of action (consequence of multiple-frequency wave packets at the providing with high concentration of the dispersed phase of more than 10% turns) for the realization of the second stage of dispersion (breaking of preliminary formed coarse-dispersed drops).

To provide maximum efficiency of the secondary dispersion it is determined required energy of the wave packets on the base of the drop breakup model described below.

4.2. Determination of energy of the wave packets necessary for the dispersion of liquid phase

For determining of the different frequencies wave packets required for the dispersion of liquid phase it was analyzed the drop breakup model with the modification of boundary condition at large distances from the drop.

$$u = \begin{cases} \sqrt{\frac{2e}{\rho}}\sin(\omega t); & t \le \tau \\ \sqrt{\frac{2e}{\rho}}\sin(2\omega(t-\tau)); & \tau < t \le 2\tau \\ 0; & t > 2\tau \end{cases}; \quad (7)$$

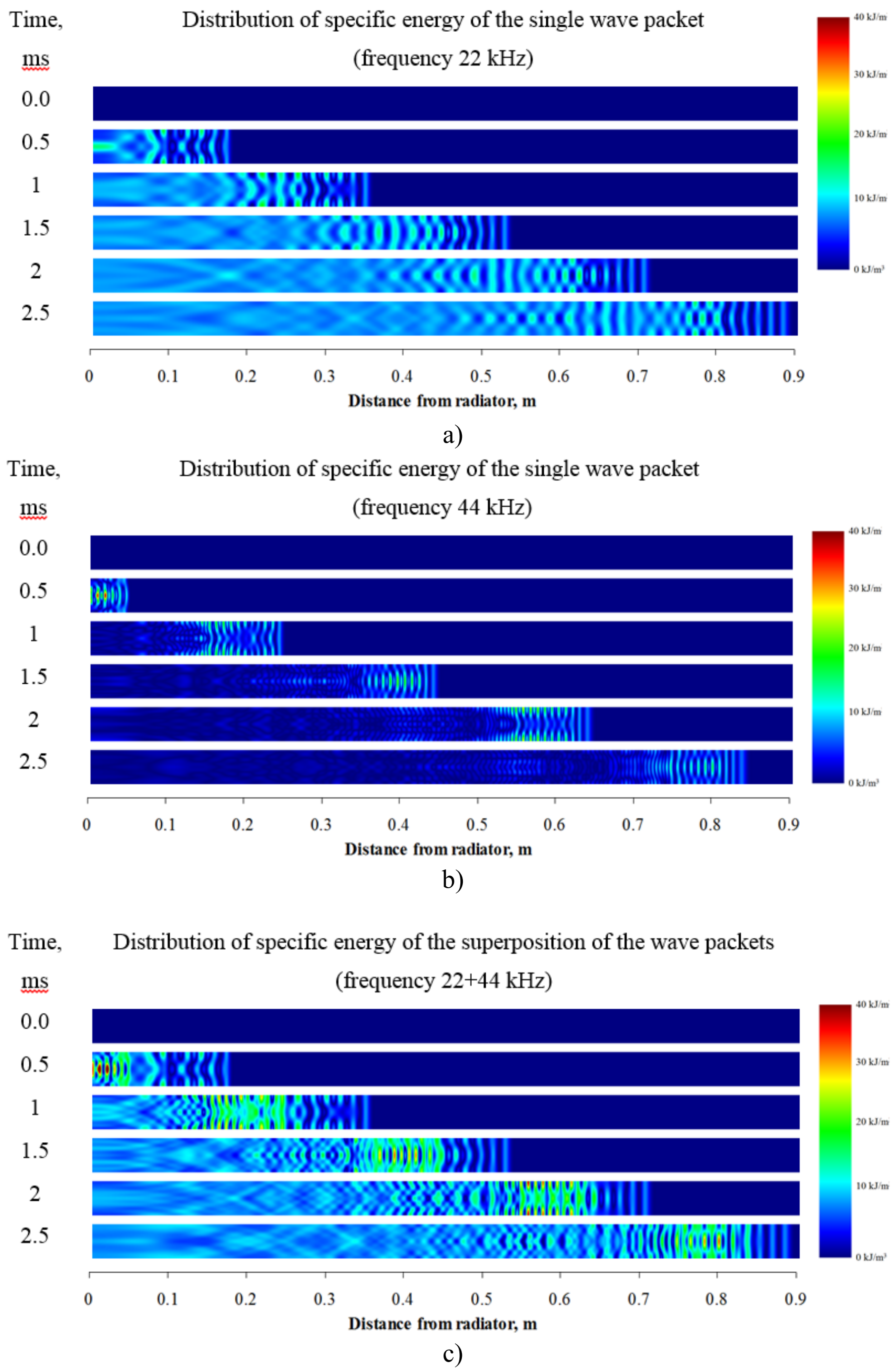


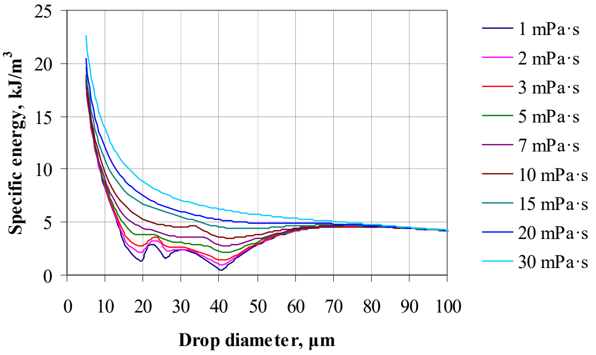
Figure 8. Distributions of specific vibration energy in different instants of time under the action of the wave packets in the extensive channel of 900 mm long
(Ultrasonic radiator of 20 mm in diameter is placed at the left end of the channel)

where e is the energy of the single wave packet, J/m^3; ρ is the density of the carrying medium, kg/m^3; ω is the vibration frequency of the first wave packet, kHz; τ is the duration of the wave packet, s.

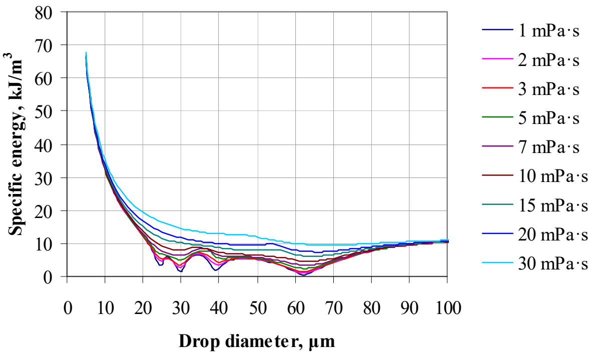
Figure 9 shows the dependences of minimum energy of the single wave packet, which necessary for drop breaking under the action of 2 interchangeable wave packets with the frequencies of 22 and 44 kHz generated by one radiator.

Presented dependence proves the decrease of energy of single wave packet, which is necessary for drop breakup, in more than 20 kJ/m^3 even under the action of two packets with different frequencies. From obtained dependences it is follows that for the breakup of large drop with the sizes of 30…100 micron up to small sizes energy of one packet from 1 to 10 kJ/m^3 will be sufficient.

Moreover, under the action of the wave packets with different frequencies it is observed quadratic increase of the amount of resonance drop diameters with the rise of the number of the wave packets. It means, that the action by the wave packets at 2 frequencies leads to the appearance of 4 resonance diameters, as vibration of the drop includes 4 temporal harmonics with the highest amplitudes at the frequencies of 22, 44, 66 and 88 kHz. It is proved by the fact that force acting on the drop is proportional to square of relative speed between the carrying medium flow and the drop. So, the action at several frequencies allows covering all the range of changes of the resonance frequency of the drop.



a) 20 mN/m



b) 72 mN/m

Figure 9. Dependences of energy of single wave packet on the drop diameter at different viscosities and surface tensions of liquid (frequency 22+44 kHz)

Thus, the proposed method of action for the secondary dispersion is sufficient to use the radiator, which is able to generate vibration energy of 1…10 kJ/m^3 in continuous air medium (the acoustic power is no more 2 kW at the radiating surface are of 0.08 m^2). The production of such radiator (in spite of the radiator generated vibrations with energy of 20…160 kJ/m^3) can be technically realized [28].

5. CONCLUSION

The proposed method of the ultrasonic dispersion provides increasing of productivity of generation of high-dispersed liquid phase (aerosol in the carrying gas medium or emulsion in the carrying liquid medium) with the size of the drops of less than 10 micron and consists two stages:

– preliminary formation of coarse-dispersed drops from the free surface of liquid to be dispersed;

– breakup of formed drops in smaller ones under the action of high-intensity ultrasonic field generating vibrations of the drop walls.

To provide maximum productivity of dispersion up to required drop diameter (less than 10 micron) necessary energy of the ultrasonic field was determined at the second stage of the process on the base of developed models of propagation of ultrasonic vibrations and evolution of drop size in dispersed medium.

As a result of the model analysis it is ascertained, that at the action of monofrequency sinusoidal vibrations minimum energy of the ultrasonic field required for the drop breakup is more than 20 kJ/m^3 for coarse-dispersed drops (80…100 micron) and more than 160 kJ/m^3 for high-dispersed drops (1…15 micron). It is technically impossible to provide such high energies by the modern radiators, as radiator power should be more than 40 kW.

For providing energy required for the drop breakup at lower radiator power method of the formation of field based on the radiation of consequence of the wave packets of finite duration and multiple frequency was proposed. The method of action allows reducing power requirements to the ultrasonic radiator for the realization of the drop dispersion (acoustic power of less than 2 kW).

Thus, proposed method of drop dispersion and generation of the ultrasonic field assures the productivity increase of formation of high-dispersed liquid phase in comparison with one-stage ultrasonic dispersion.

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REFERENCES

[1] Khmelev V.N., Shalunov A.V., Galakhov A.N., Khmelev M.V., andGolykh R.N. The control of ultrasonic coagulation of dispersed nanoscale particles печ. 14th International Conference of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2013: Conference Proceedings. – Novosibirsk: NSTU, 2013. – P. 166-170.

[2] Khmelev V.N., Golykh R.N., Shalunov A.V., Bazhin V.E.,and Nesterov V.A. Determination of Optimum Conditions of Ultrasonic Cavitation Treatment of High-viscous and Non-newtonian liquid media печ. 16th International Conference of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2015: Conference Proceedings. – Novosibirsk: NSTU, 2015. – P. 208-212.

[3] Khmelev V.N., Golykh R.N., Shalunov A.V., Khmelev S.S., andKarzakova K.A. Determination of ultrasonic effect mode

providing formation of cavitation area in high-viscous and non-newtonian liquids печ. 15th International Conference of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2014: Conference Proceedings. – Novosibirsk: NSTU, 2014. – P. 203-207.

[4] Rotor impulse apparatuses for the obtaining of systems “liquid-liquid”: patent 2299091 RF MPK B01F3/08, B01F7/28 / Sakovich. G.V., Vasilishin M.S., Kukhlenko A.A., Sysolyatin S.V., Karpov A.G. (RF), patent holder: The Institute of Problems of Chemical and Energy Technologies of Siberian Branch of Russian Academy of Sciences (RF) claimed 2005135595/15 at 16.11.2005, published 20.05.2007.

[5] Yasuda K., Honma H., Asakura Y., Koda S. Effect of Frequency on Ultrasonic Atomization. *Proceedings of Symposium on Ultrasonic Electronics*. 2010. Vol. 31. P. 363–364.

[6] Tsai S.C., Song Y.L., Tsai C.S., Yang C.C., Chiu W.Y., Lin H.M. Ultrasonic spray pyrolysis for nanoparticles synthesis. *Journal of Materials Science*. 2004. 39. P. 3647–3657.

[7] Dalmoro A., Angela Barba A., d’Amore M. Analysis of Size Correlations for Microdroplets Produced by Ultrasonic Atomization. *The Scientific World Journal.* 2013. 7 p.

[8] Asami T., Yakou R., Ono T., Mlura H. Ultrasonic atomization by difference between vibration displacements of two circular vibrating plates. *Journal of Mechanical Engineering and Automation*. 2016. Vol 2. Issue 6. P. 30–35.

[9] Khmelev V.N., Shalunov A.V., and, Smerdina E.S. The Cavitation Spraying of the Viscous Liquids / Conference proceedings 7th Annual International Workshop and Tutorials on Electron Devices and Materials 2006, EDM, 01 – 05 June,2006. – Novosibirsk: NSTU, 2006. – P. 269 – 273.

[10] Khmelev V.N., Golykh R.N., andShalunov A.V. Optimization of these modes and conditions of ultrasonic influence on various technological mediums by mathematical modeling. EDM'2012: Conference Proceedings. Novosibirsk, 2012. P.124–134.

[11] Khmelev V.N., Shalunov A.V., Nesterov V.A., Abramenko D.S., Genne D.V., andDorovskikh R.S. Automated line for ultrasonic spraying of anticoagulant into the blood collection tubes. EDM'2014: Conference Proceedings. Novosibirsk, 2014. P. 181–186.

[12] Khmelev V.N., Golykh R.N., Shalunov A.V., Shalunova A.V., andGenne D.V. The investigation of modes of ultrasonic influence for atomization of liquids with specified dispersivity and productivity. International Conference and Seminar on Micro / Nanotechnologies and Electron Devices. EDM'2012: Conference Proceedings. Novosibirsk, 2012. P. 188-194.

[13] Kapelukhovskaya A.A. Intensification of the emulsification with the use of hydrodynamic radiators / Materials of the 6th international scientific and technical conference “Technics and technologies of petrochemical and gas-and-oil production” - Omsk: OmGTU publishing, 2016. – P. 76.

[14] Canselier J.P., Delmas H., Wilhelm A.M., Abismail B. Ultrasound emulsification – An Overview // *Journal of Dispersion Science and Technology*, 2002. – 23(1-3). – P. 333-349.

[15] Chalothorn K., Warisnoicharoen W. Ultrasonic emulsification of whey protein isolate-stabilized nanoemulsions containing omega-3 oil from plant seed // *American journal of food technology*, 2012. – 7(9). – P. 532-541.

[16] Yoshiyuki Tominaga, Takuya Harada, Takefumi Kanda, Koichi Suzumori, Tautomu Ono, Sotaro Iwabuchi, Kazuyuki Ito, Ken-ichi Ogawara, KazutakaHigaki, andYuta Yoshizawa (Okayama Univ.) The condition of an emulsion generation by using an ultrasonic vibration and a microchannel // Proceedings of Symposium on Ultrasonic Electronics, 2010. – Vol. 31. – P. 233-234.

[17] Tomas Hielscher. Ultrasonic production of nano-size dispersions and emulsions // ENS’05, Paris, France, 14-16 December 2005. – 6 p.

[18] M. Hryniewicka. Ultrasound-assisted emulsification microextraction in the environmental and food analysis // *PhD Interdisciplinary Journal*, 2015. – 1. – P. 185-191.

[19] Galakhov, A.N., Khmelev V.N., Golykh R.N., Shalunov A.V., Nesterov V.A., andShalunova A.V. Study of the process of liquid atomization from the ultrasonic disk radiator / 14th International Conference of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2013: Conference Proceedings. – Novosibirsk: NSTU, 2013. – P.119-122.

[20] Ultrasonic flowing reactor [Text]: patent 2403085 RF MPK B01J19/10 / Borisov U.A., Leonov G.V., Khmelev V.N., Abramenko D.S., Khmelev S.S., Shalunov A.V. (RF) patent holder: Altai State Technical University (RF) claimed 2009115487/05 at 23.04.2009, published in 10.11.2010.

[21] Lang, R.J. Ultrasonic atomization of liquids. *The Journal of the Acoustical Society of America*. 1962. V. 34. P. 6–8.

[22] Rozenberg, L.D. *Physical foundation of ultrasonic technology*, M.: Science. 1970. In Russian.

[23] LeeaM.W., ParkaJ.J., FaridbM.M., and, YoonaS.S. Comparison and correction of the drop breakup models for stochastic dilute spray flow. *Applied Mathematical Modelling*. – 2012. – Vol. 36. – Iss. 9. – P. 4512–4520.

[24] Kupershtokh, A.L. Method of Boltzmann lattice equation for modeling of two-phase systems of liquid-vapor type / A.L. Kupershtokh // Modern Science. – 2010. – №2. – P. 56–63.

[25] Khmelev V.N., Golykh R.N., Khmelev M.V., Shakura V.A., Shalunov A.V., and Barsukov R.V. Evaluation of Optimum Modes of Ultrasonic Pulsed Influence for Coagulation In Liquid-Dispersed Medium // 17th International conference on micro/nanotechnologies and electron devices EDM 2016. - 2016. - P.225-231.

[26] Khmelev V.N., Shalunov A.V., Golykh R.N., Shalunova K.V., Galakhov A.N., and Nesterov V.A. Revealing of optimum modes of ultrasonic coagulation of submicron particles and determining of the shape of the aggregates by mathematical modeling // 15th International Conference of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2014: Conference Proceedings. – Novosibirsk: NSTU, 2014. – P. 208-212.

[27] Khmelev V.N., Shalunov A.V., Golykh R.N., and Shalunova K.V. Theoretical Study of Acoustic Coagulation of Gas-dispersed Systems // International Conference and Seminar on Micro / Nanotechnologies and Electron Devices. EDM'2010: Conference Proceedings. – Novosibirsk: NSTU, 2010. –P. 328-333.

[28] Nigmatulin R.I. *The dynamics of multi-phase media*. V. 1, 2. – Moscow: Science, 1987.

[29] Khmelev V.N., Shalunov A.V., Dorovskikh R.S., Golykh R.N., and V.A. Nesterov. The Measurements of Acoustic Power Introduced into Gas Medium by the Ultrasonic Apparatuses with the Disk-Type Radiators // 17th International conference on micro/nanotechnologies and electron devices EDM 2016. - 2016. - P.246-250.

[30] Sheng C.D. and ShenX.L. Modelling Acoustic Agglomeration Processes Using Direct Simulation Monte Carlo Method.*Journal of Aerosol Science*. – 2006. – Issue 37. – P. 16–36.

[31] Xie W., Li Rkp and Lu X. Pulsed ultrasound assisted dehydration of waste oil // *Ultrason Sonochem*, 2015, Sep 26, pp. 136-141.