American Journal of Engineering Research (AJER) 2017
American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-6, Issue-8, pp-184-194
www.ajer.org
Research Paper Open Access

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

*V.N. Khmelev[1], A.V. Shalunov[1], R.N. Golykh[1], R.S. Dorovskikh[1], V.A. Nesterov[1]
[1]*Biysk Technological Institute (branch) of Altay State Technical University named after I.I. Polzunov, Russia*
Corresponding Author: V.N. Khmelev[1]

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. At pulsed influence the required radiator power is reduced up to 2 kW at radiation surface area 800 cm^2.*

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

Date of Submission: 28-07-2017 Date of acceptance: 24-08-2017

I. INTRODUCTION

The application of the heterogeneous systems with high-dispersed liquid phase is the promising method of accommodation disinfection, neutralization of dangerous aerosols, development of the new kinds of fuels and increase of energy datum of the existing ones, drying of various materials, etc. The use efficiency of the heterogeneous systems with high-dispersed liquid phase for the solution of different tasks [1-4] is first of all caused by larger specific mass phase interface in comparison with the systems having film or foam structures.

It is known, that spraying of even 2 ml of disinfecting aerosol containing polyhexamethylene guanidine hydrochloride 0.16% and didecyldimethylammonium chloride (0.03%) ("Aeron") provides disinfection of 1 m^3 of air. Another example is that dispersion of 1% of water [3] in the hydrocarbon fuel (petroleum, diesel, furnace fuel oil, etc.) increases efficiency of the internal-combustion engines and atomizing burners in more than 5% (if the size of the emulsion drops is 2…3 μm).

At present widely applied methods of generation of dispersion phase in liquids and gases are based on the either introduction of the additives – surface active substances or emulsifiers or hydrodynamic phenomenon – mechanical, hydrodynamic (atomizers), rotor-impulse [4], etc., which were developed at the end of 19th – in the beginning of 20th centuries. However the most widely spread methods allow efficiently generating rather coarsely dispersed systems with the drop size of more than 100 μm. The attempts of generation of high-dispersed systems (with the drop size of less than 10 μm) by the use of traditional methods led to disproportional growth of power inputs (the efficiency of the dispersion process was less than 0.1%) or to secondary coagulation of drops. One of the most promising approach to the formation of liquid dispersed phase is the low-frequency ultrasonic action (at the frequencies of 22…250 kHz), which allows accomplishing liquid dispersion both in gaseous carrying phase (spraying) and in the other liquid (emulsification).

The ultrasonic dispersion has following advantages:
– the absence of necessity to use the additives (emulsifiers, surface active substances or spraying agents);
– the possibility of dispersion of high-viscous liquids;
– small range of the formed drop sizes relatively 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 [9-11] (Russian Federation) – for spraying; Omsk State Technical University [12] (Russian Federation), École nationale supérieure de techniques avancées [13] (France), Chulalongkorn University [14] (Thailand), Okayama University [15] (Japan), Hielscher Gmbh. [16] (Germany), Institute of Chemistry [17] (Poland) – for emulsification.

However, in spite of all advantages and great attention to the problem from the researchers [1-3, 5-17] the ultrasonic dispersion is not widely applied in industry. It is connected with the necessity to solve two mutually exclusive tasks – to provide high efficiency and simultaneously high dispersion of formed drop liquids. At that the productivity according to theoretically and experimentally obtained results [5-17] is inversely proportional to the drop size and it is insufficient for the industrial application at the generation of high-dispersed drops.

At present maximum achieved productivity of the drop formation with the size of 60…100 μm is 1 ton per hour due to the use of the ultrasonic radiators with the increased surface area (up to 800 cm^2) [18, 19], and the drops with the size of less than 10 μm is no more than 4 l/h.

Such a low productivity of high-dispersed drop formation is concerned first of all with the fact that the ultrasonic action was carried out in a cavitation mode, when under the action of cavitation the drops tear off from the free surface of liquid bordering with the gaseous phase (spraying) or with the other liquid (emulsification).

At the appearance of cavitation in dispersed liquid phase small part of vibration energy (less than 1%) is directly spent on the conversion of liquid into disperse state. At that the most part of energy is used for the heating of liquid due to the local temperature growth in the microscopic nuclei of the cavitation bubbles up to 5000 K (in the moment of coalescence) [2, 3].Thus the task of searching new approaches to the formation of high-dispersed liquid phase with the increased productivity in the ultrasonic fields is up to date.

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

In a view of insufficient efficiency of cavitation for the drop generation the authors propose the method of high-dispersed liquid phase obtaining based on non-cavitation ultrasonic action. Proposed method is that the walls of preliminary formed coarsely dispersed drops excite vibrations. When the amplitude of drop wall vibrations exceeds specified threshold value (half of the drop radius), it occurs their break up to required sizes (less than 10 μm). Thus, proposed method of dispersion consists of two stages, which are illustrated by Fig.1 – formation of coarsely dispersed drops from the free surface of liquid to be dispersed, breaking of coarsely dispersed drops into smaller ones.

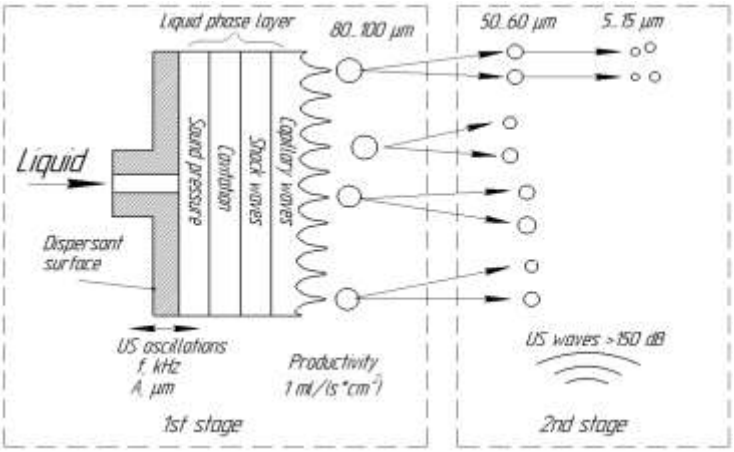


Figure 1 – Method of highly productive formation of high-dispersed drops in the ultrasonic fields

Proposed method of dispersion allows increasing productivity of the formation of high-dispersed liquid phase in several times in comparison with one-stage dispersion in the cavitation mode due to:

– possibility of obtaining required size of small drops (less than 10 μm) from large drops (40 – 80 μm) obtained at the primary dispersion. According to the studies carried out before [5-17] the dispersion of large drops is

characterized higher productivity up to 200 times in comparison with the small ones. At that the breaking of large drops into small ones takes no more than several tens of periods of ultrasonic vibrations (no more than 0.2 s).

– preserving of the dispersion productivity at the breaking of large drops into small ones in the frames of the second stage in a view of mass conservation law. Moreover two-stage method requires lower power inputs for the formation of dispersed phase in comparison with one-stage one due to low energy required for the preliminary generation of coarsely dispersed drops and non-cavitation influence of the ultrasonic vibrations at the second stage of the dispersion.To provide maximum efficiency of proposed two-stage method it is necessary to reveal optimum modes of the ultrasonic action on the base of complex studies of the processes of vibration excitation of the drop walls and the evolution of the dispersion phase in the ultrasonic fields. Further it is described the model of drop walls vibrations excited under the action of high-intensity ultrasonic fields.

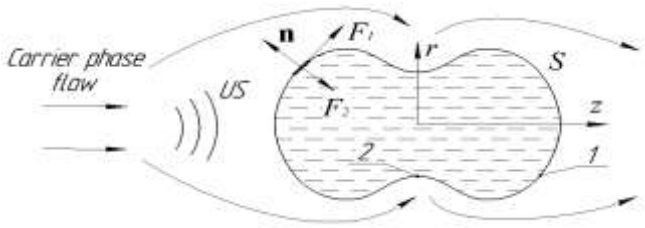
III. PHYSICAL-MATHEMATICAL MODEL OF VIBRATION EXCITATION OF THE DROP WALLS IN THE HIGH-INTENSITY ULTRASONIC FIELDS

The model is based on the calculation of liquid motion in the volume of the drop under the action of the following forces (Fig.2) [20]:

– pressure difference in the vibrating flow of the carrying phase;

– differences of the surface tension forces at the wavelike excitations of the drop wall (F_2);

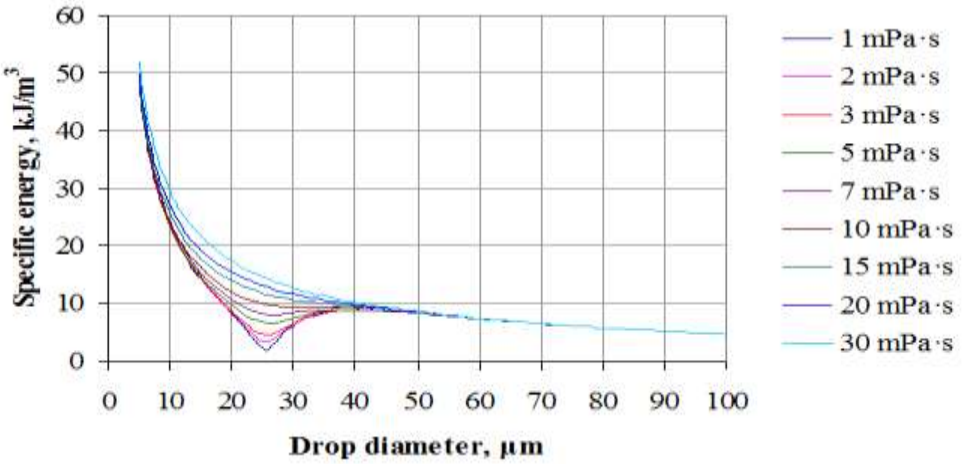
– forces of viscous tension at the motion of the walls with the non-zero velocity (F_1).



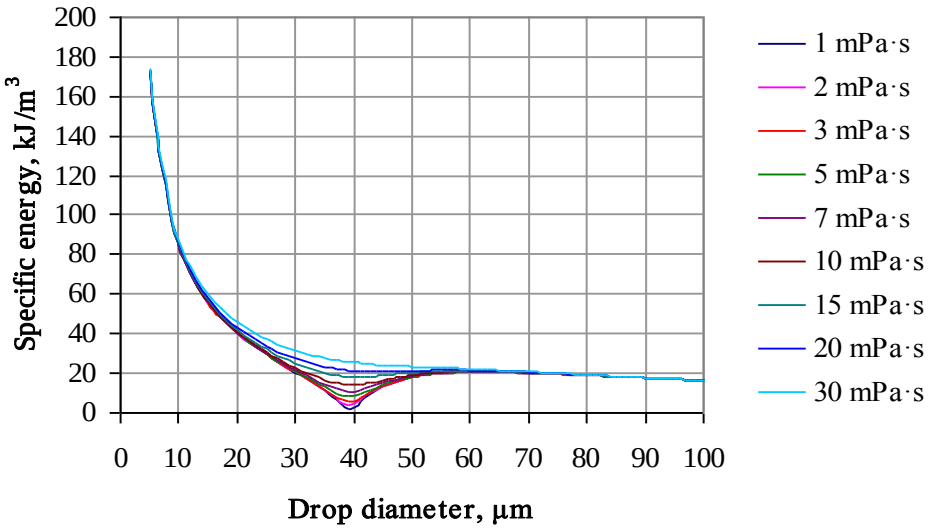
n – normal vector to the drop wall; *S* – surface of the drop; (*r*, *z*) – axes of the cylinder coordinates

Figure 2 – Scheme of the drop deformation in the ultrasonic field

For the calculation of change of the drop vibration form the numerical method of Boltzmann lattice equations [21] based on the consideration of liquid flow as a motion of pseudoparticle ensemble having some cumulative distribution curves on the discrete velocities $N_k(\boldsymbol{x},t)$ was used. $N_k(\boldsymbol{x},t)d\boldsymbol{x}$ is the number of the pseudoparticles $x > d/4$, when Weber number exceeds critical value $We > We_{crit} = 6$ (the force of surface tension in the central part of the drop 1 is greater than the force of the surface tension in the peripheral area 2 (see Fig. 2) due to the local drop thinning) [20]. It is evident, that maximum drop deformation is in proportion to entered energy of vibrations. That is why for the drop breaking the energy of vibrations should exceed some threshold value, at which $x = d/4$. Further we show the dependences of minimum energy of the ultrasonic field (the ratio of vibration intensity to sound velocity in the carrying phase $e=I/c$), which is necessary for the realization of the elementary act of the drop breaking under the action of sinusoidal vibrations of one frequency (Fig. 3 and Fig. 4).

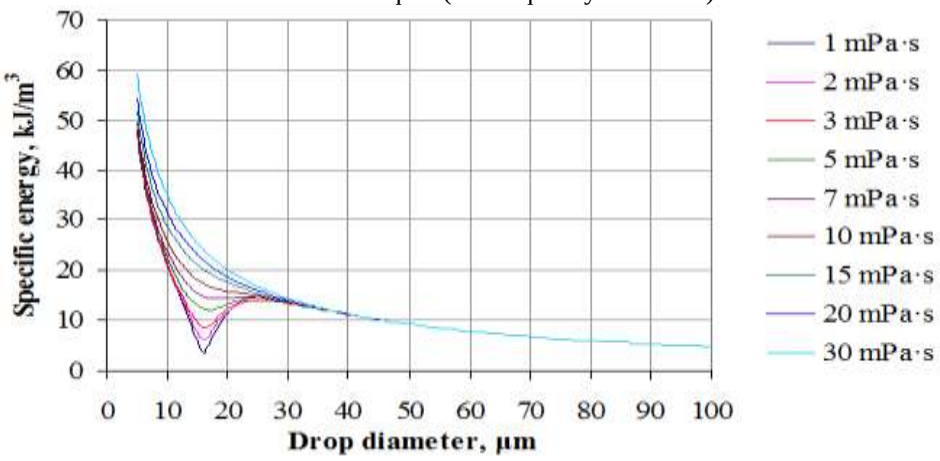


a) 20 mN/m

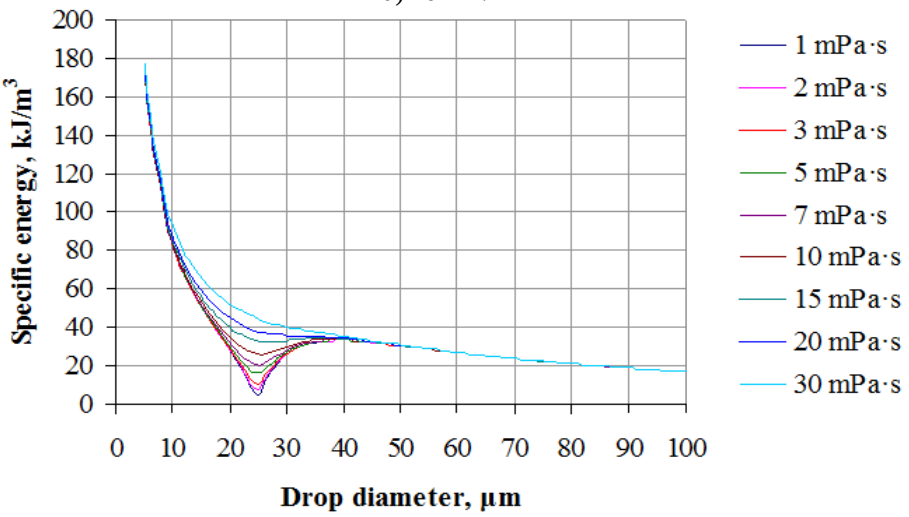


b) 72 mN/m

Figure 3 – 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 4 – 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 diameters, at which vibration energy necessary for the drop breaking achieves local minimum (less than 10 kJ/m^3). These diameters 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. At that 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.

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. That is why it is necessary to consider the character of the vibration energy dependence outside the resonance. Outside the resonance the vibration energy is in 20…160 kJ/m^3 higher than in the resonance area. From the graph in Fig.4 it follows, that the threshold vibration energy rises with the reduction of the drop diameter. It is caused by the growth of the capillary forces, which prevent the deformation of the drop.

According to the results of the calculations it is determined, that the characteristics of the ultrasonic field for the dispersion of liquid phase should satisfy following requirements:

1) specific energy of generated field should be more than 20 kJ/m^3, that requires the acoustic power of the radiator of more than 40 kW defined as $P=ecS$ (e is the specific vibration energy, J/m^3; c is the sound velocity in the carrying phase, m/s; S is the area of the radiating surface) at the area of the radiating surface from S=800 cm^2;

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

2) at the dispersion in the carrying gas phase 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 (at the acoustic power of the radiator of no more than 2 kW [18, 19] and the area of the radiating surface from 800 cm^2) even at the formation of resonance conditions of reflection and propagation of the ultrasonic field. Thus, it is impossible to generate high-intensity field at low power of the radiator by the action of sinusoidal vibrations consisting of one harmonics.

It is proposed the method of action based on the formation of the chain of wave packets with different frequencies, which is described further.

IV. METHOD OF GENERATION OF ULTRASONIC FIELD REQUIRED FOR THE DISPERSION OF LIQUID PHASE

For the generation of high-intensity ultrasonic field with the characteristic, which are enough for the dispersion of drops, at relatively low 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 the chain of finite-length wave packets (no more than 10 ms) at multiple frequencies (ultrasonic impulses). Owing to intermodal dispersion caused by the presence of heterogeneous inclusions (liquid drops) in multiphase medium these packets will have different speed of propagation and at some distance from the radiator they will make superposition.

This method of generation of the ultrasonic field has following advantages:

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

– possibility to control the position of the zone, in which dispersion occurs;

– absence of undesirable cavitation phenomenon in a liquid to be dispersed due to the finite length of impulse [22];

– possibility to increase vibration amplitude owing to superposition of the wave packets irrespective of the geometry of the technological volume and the form of the radiator;

– absence of particle coagulation due to small finite length of the impulse (no more than 10 ms), as the mean time required for joining of two particles is high in comparison with the length of the single impulse and it is more than 0.5 s [23, 24].

To create the conditions for the formation of high-intensity ultrasonic field it is necessary to carry out the analysis of propagation of wave packets in gaseous medium taking into account the influence of liquid

drops. The analysis of propagation of the wave packets was carried out on the base of the wave equation obtained from the general equations of gas-drop medium dynamics [25]:

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

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

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

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

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

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

where ρ_{10} is the air density, kg/m^3; ρ_{20} is the liquid density, kg/m^3; α_{10} is the balanced volumetric air content; α_{20} is the balanced volumetric liquid content; c is the sound velocity in air; v_1 is the air velocity, m/s; v_2 is the liquid velocity, m/s; μ is the air viscosity, Pa·s; a is the radius of the liquid drop, m; p_1 is the air pressure, Pa; α_1 is the disturbance of volumetric air content; α_{20} is the disturbance of volumetric liquid content.

Obtained wave equation includes non-zero right part taking into consideration the influence of liquid drops and representing double integral from the prehistory of change of sound pressure with exponentially decreasing weight coefficients:

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

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

The calculations of sound velocity in the medium with disperse liquid phase carried out on the base this equation allow determine, that at the volumetric aerosol concentration in air of no less than 10% the sound velocity increases up to 1.5 time at the growth of the frequency from 22 to 66 kHz (Fig.5).

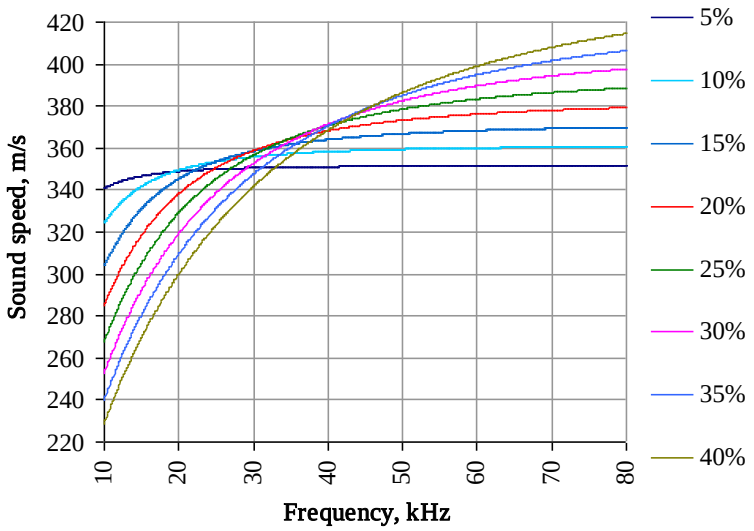


Figure 5 – Dependence of sound velocity on the frequency of the ultrasonic waves at different volumetric content of water aerosol (the drop diameter is 20 μm)

At such difference of sound velocities the superposition of the wave packets occurs at the distance of no more than 400 cm from the surface of the radiator (Fig.6).

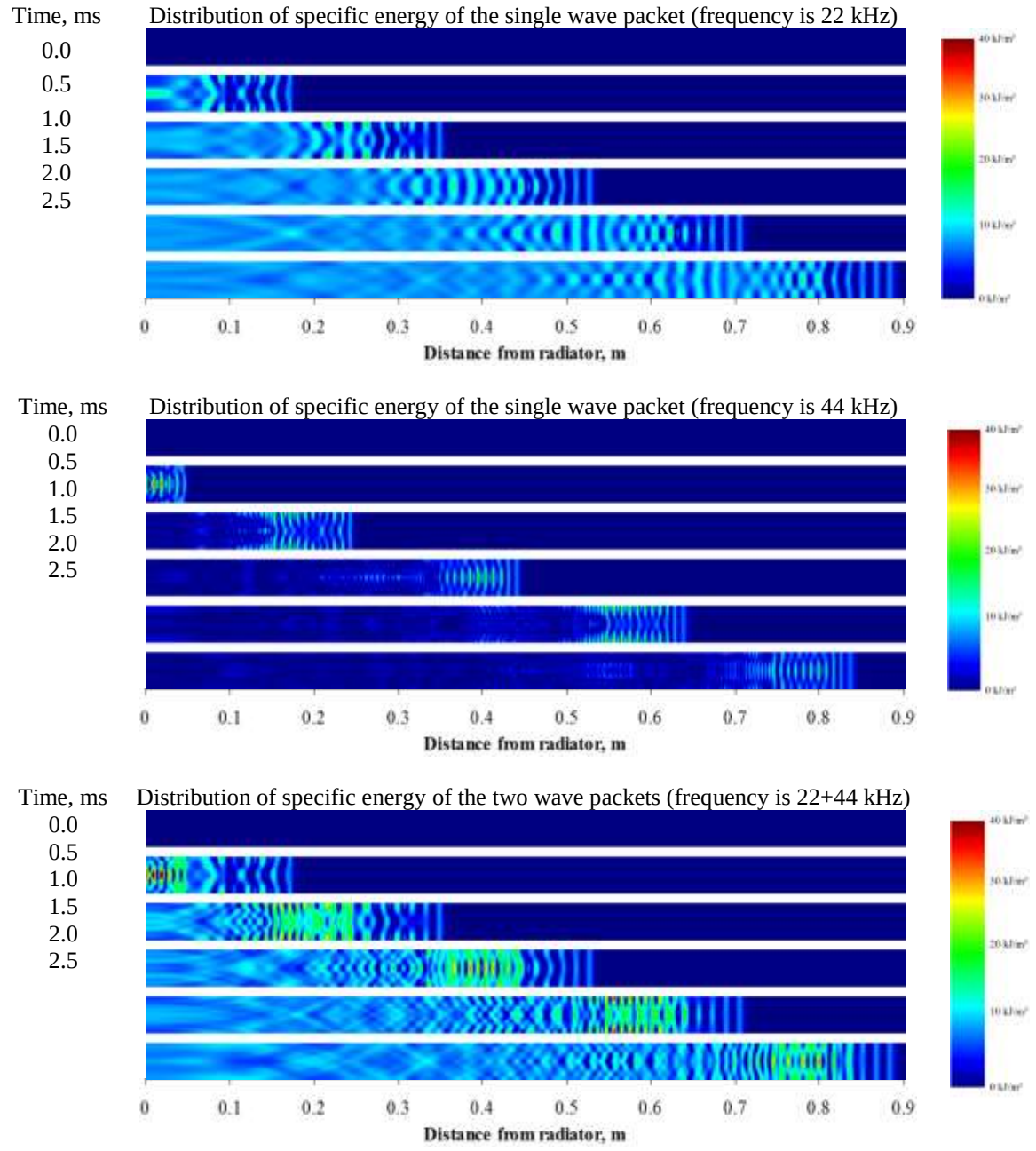


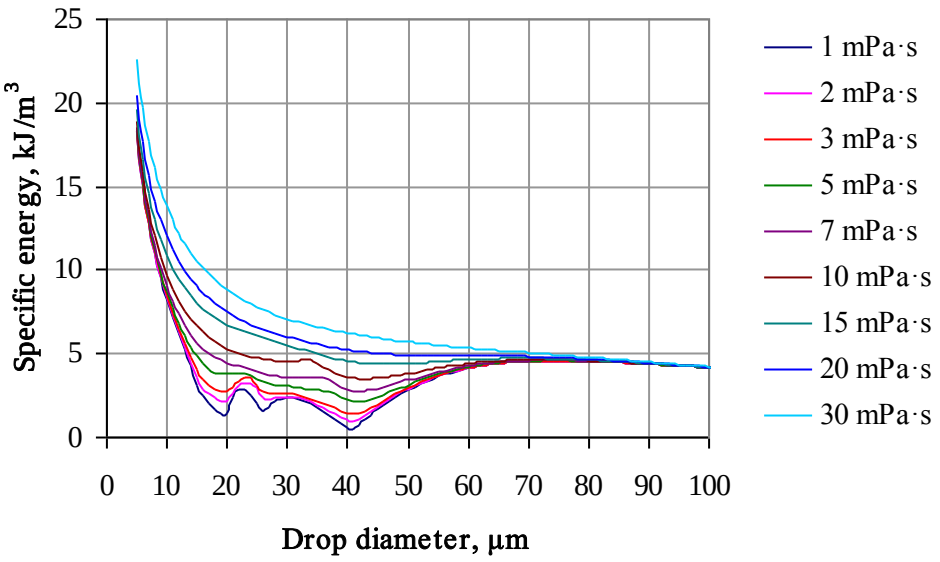
Figure 6 – Distributions of specific vibration energy in different moments of time at the action of the wave packets in extensive channel with the length of 900 mm (the ultrasonic radiator with the diameter of 20 mm is placed at the left end of the channel)

Thus, it is determined principal possibility of ultrasonic energy concentration with the help of proposed method of action (chain of wave packets with different frequencies at providing high concentration of dispersed phase of more than 10%) for the realization of the second dispersion stage (breaking of preliminary formed coarsely dispersed drops).

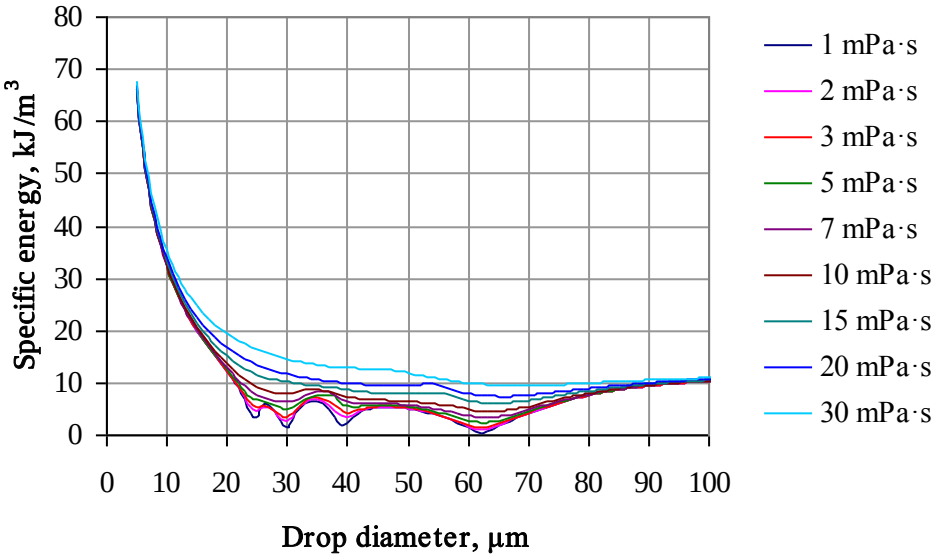
To provide maximum efficiency of the secondary dispersion we determine optimum action modes by the wave packets on the base of previously described model of the drop breaking.

V. OPTIMUM CHARACTERISTICS OF HIGH-INTENSITY ULTRASONIC FIELD NECESSARY FOR THE DISPERSION OF LIQUID PHASE

Fig.7 shows the dependences of minimum energy of the single wave packet necessary for drop breaking under the action of 2 alternating packets with the frequencies of 22 and 44 kHz generated by one radiator.



a) 20 mN/m



b) 72 mN/m

Figure 7 – Dependences of the energy of the single wave packet on the drop diameter at different viscosities and surface tensions of liquid (the frequency is 22+44 kHz)

Presented dependences prove decrease of wave packet energy, which is necessary for drop breaking, in more than 20 kJ/m^3 even under the action of two packets with different frequencies. As the results show, 60 kJ/m^3 is sufficient for breaking the drops up to the sizes of less than 5 μm.

Moreover, under the action wave packets with different frequencies it can be observed quadratic increase of the number of the resonance drop diameters with the growth of the packets number in series, as the force acting on the drop from the side of the gas flow is in proportion to the square of the gas velocity. It means that the influence by the wave packets at two frequencies leads to the formation of four resonance diameters, as

the drop vibration includes four temporal harmonics with the highest amplitudes at the frequencies of 22, 44, 66 and 88 kHz. Last statement is caused by the fact that the force from the side of gas flow acting on the drop is in proportion to the square of flow velocity relatively to the drop. Thus, the action at several frequencies allows surpassing all range of changes of the drop resonance frequency at its breaking and evaporation that provides additional decrease of vibration energy, which should be generated by the radiator in the dispersed system.

From presented dependences it follows, that at proposed method of action for the secondary spraying it will be enough to apply the radiator, which is able to generate vibration energy of 1…10 kJ/m^3 (acoustic power of no more than 2 kW at the area of the radiating surface of 800 cm^2) in continuous air medium. The production of such radiator (in contrast to the radiator with the vibration energy of 20…160 kJ/m^3) can be technically realized [26].

To determine the dispersion efficiency at found modes of the ultrasonic field we carry out comparative analysis of the time of drop breaking and the time, which is required for the appearance of the coagulation preventing dispersion.

For this purpose it is calculated the evolution of the drop diameter in the course of time. At the calculation of liquid dispersed phase evolution under the action of ultrasonic vibrations we can see breaking of one drop (choosing each time one drop from two new ones formed as a result of elementary breaking act).
Let elementary breaking acts be realized in the moments of time t_1, t_2, …, t_n, where $t_k \leq t_{k+1}$.

Assuming breaking of the drop for two drops at each breaking act following difference equation is true for the drop diameter, which is caused by the fact that the diameter of new drops obtained during the breaking is in $\sqrt[3]{2}$ less than the diameter of the initial drop.

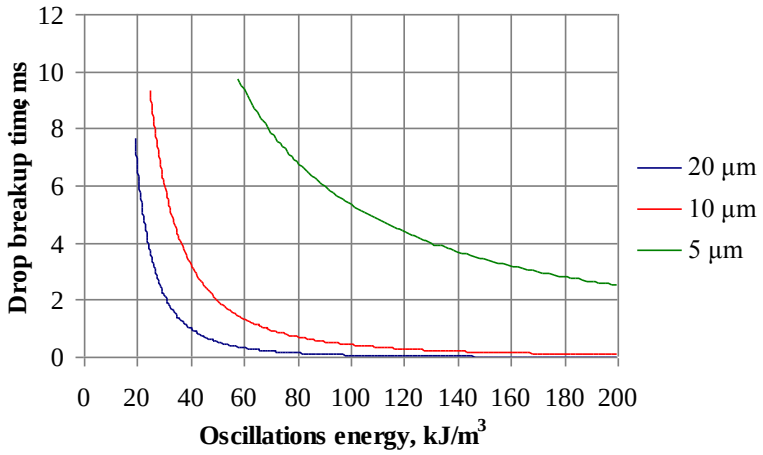
$$\frac{d(t_{n+1}) - d(t_n)}{t_{n+1} - t_n} = -\frac{d(t_n)}{t_{n+1} - t_n}\left(1 - \frac{1}{\sqrt[3]{2}}\right)$$

At rather large number of elementary breaking acts and after the application of averaging operation of the random quantities representing the moments of time of the acts t_k the following differential equation can be obtained:

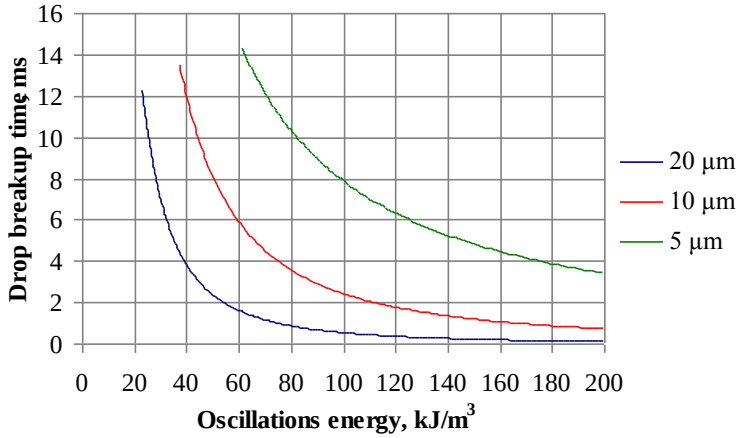
$$\frac{\partial \langle d \rangle}{\partial t} = -\frac{\langle d \rangle}{\langle \tau \rangle}\left(1 - \frac{1}{\sqrt[3]{2}}\right);$$

where $\langle \tau \rangle$ is the mean time interval between elementary acts of the drop breaking defined by the comparison of the absolute value of the drop deformation with the threshold deformation $\langle d \rangle / 4$, at which the breaking takes place, s.

Given equation allows calculating time, which is necessary for the drop breaking up to required size depending on the parameters of the ultrasonic field. Fig.8 shows the dependences of drop breaking time on energy of the single wave packet at different final drop diameters and viscosities of the liquid to be dispersed. The dependences were made for the case of action of the wave packet superposition of two frequencies 22+44 kHz.



a) 1 mPa·s



b) 10 mPa·s

Figure 8 – Dependences of the drop diameter on time at different energies of the single wave packets and viscosities of liquid to be dispersed

As it follows from presented dependences at determined parameters of generated ultrasonic field the drop breaking time is less than 0.015 s, i.e. less than the time required for the secondary coagulation of particles (more than 100 s to coagulate more than 50 % of the initial particles [27]). At that the action during the certain period of time of the drop breaking of less than 0.015 s allows increasing maximum energy in 3 times, at which pre-cavitation mode will be remained at the dispersion in the carrying liquid phase [22, 28].

These facts prove the efficiency of proposed method of high-dispersed phase formation.

VI. CONCLUSION

It was proposed the method of ultrasonic dispersion providing productivity growth of generation of high-dispersed liquid phase (aerosol in the carrying gas phase or emulsion in the carrying liquid phase) with the drop size of less than 10 μm and consisting of two stages:

– preliminary formation of coarsely dispersed drop from the free surface of dispersed liquid;

– breaking of preliminary formed drops into smaller ones under the action of high-intensity ultrasonic field exciting vibrations of the drop walls.

To provide maximum productivity of the dispersion to required drop diameter (less than 10 μm) it was carried out complex study of optimum modes of high-intensity ultrasonic field generation at the second stage of the process on the base of the models of the ultrasonic vibration propagation and the evolution of the drop size in dispersed medium. As a result of the model analysis it was determined, that under the action of mono-frequency sinusoidal vibrations the minimum energy of the ultrasonic filed required for the drop breaking was more than 20 kJ/m^3 for coarsely dispersed drops (80…100 μm) and more than 160 kJ/m^3 for high-dispersed drops (1…15 μm). Such high level of energy cannot be provided by the modern radiators, as the radiator power should be more than 40 kW at the area of the radiating surface of 800 cm^2 (the flat radiator of a round shape has the diameter of 320 mm).In order to decrease required power of the radiator it was proposed the method of the field generation based on the radiation of the chain of finite-length wave packets having multiple frequencies. Proposed method of action allowed reducing power requirements to the ultrasonic radiator for the realization of the drop dispersion (the acoustic power was less than 2 kW at the area of the radiating surface of 800 cm^2).

At the action of the chain of the wave packets the time of drop breaking up to required size (less than 10 μm) was less than 0.015 s, i.e. that was small in comparison with the time, which is necessary for the secondary drop coagulation (more than 100 s for the coagulation of 50% of drops). At that the action during calculated time of drop breaking let increase in up to 3 times maximum possible energy, at which there would be no any undesirable cavitation phenomena at the dispersion in the carrying liquid phase.

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

ACKNOWLEDGEMENTS

The reported study was supported by Russian Foundation for Basic Research (Project No. 16-38-60082 mol_a_dk).

REFERENCES

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

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

[3] V.N. Khmelev, R.N. Golykh, A.V. Shalunov, S.S. Khmelev and K.A. Karzakova, Determination of ultrasonic effect mode providing formation of cavitation area in high-viscous and non-newtonian liquids,15th International Conference of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2014: Conference Proceedings, 2014, 203-207.

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

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

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

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

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

[9] V.N. Khmelev, R.N. Golykh and A.V. Shalunov, Optimization of these modes and conditions of ultrasonic influence on various technological mediums by mathematical modeling, International Conference and Seminar on Micro / Nanotechnologies and Electron Devices. EDM'2012: Conference Proceedings, 2012, 124–134.

[10] V.N. Khmelev, A.V. Shalunov, V.A. Nesterov, D.S. Abramenko, D.V. Genne and R.S. Dorovskikh, Automated line for ultrasonic spraying of anticoagulant into the blood collection tubes, International Conference and Seminar on Micro / Nanotechnologies and Electron Devices. EDM'2014: Conference Proceedings, 2014, 181–186.

[11] V.N. Khmelev, R.N. Golykh, A.V. Shalunov, A.V. Shalunova and D.V. Genne, 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, 2012, 188-194.

[12] A.A. Kapelukhovskaya, 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", 2016, 76.

[13] J.P. Canselier, H. Delmas, A.M. Wilhelm and B. Abismail, Ultrasound emulsification – An Overview, Journal of Dispersion Science and Technology, 23(1-3), 2012, 333-349.

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

[15] Yoshiyuki Tominaga, Takuya Harada, Takefumi Kanda, Koichi Suzumori, Tautomu Ono, Sotaro Iwabuchi, Kazuyuki Ito, Ken-ichi Ogawara, Kazutaka Higaki and Yuta Yoshizawa, The condition of an emulsion generation by using an ultrasonic vibration and a microchannel, Proceedings of Symposium on Ultrasonic Electronics, 31, 2010, 233-234.

[16] Tomas Hielscher, Ultrasonic production of nano-size dispersions and emulsions, ENS'05, 2005, 6.

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

[18] A.N. Galakhov, V.N. Khmelev, R.N. Golykh, A.V. Shalunov, V.A. Nesterov and A.V. Shalunova, Study of the process of liquid atomization from the ultrasonic disk radiator, 14th, 2013, 119-122.

[19] 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. and Shalunov A.V. (RF) patent holder: Altai State Technical University (RF) claimed 2009115487/05 at 23.04.2009, published in 10.11.2010.

[20] M.W. Leea, J.J. Parka, M.M. Faridb and S.S. Yoona, Comparison and correction of the drop breakup models for stochastic dilute spray flow, Applied Mathematical Modelling, 36(9),2012, 4512–4520.

[21] A.L. Kupershtokh, Method of Boltzmann lattice equation for modeling of two-phase systems of liquid-vapor type, Modern Science, 2, 2010, 56–63.

[22] V.N. Khmelev, R.N. Golykh, M.V. Khmelev, V.A. Shakura, A.V. Shalunov and R.V. Barsukov, Evaluation of Optimum Modes of Ultrasonic Pulsed Influence for Coagulation In Liquid-Dispersed Medium, 17th International Conference of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2016: Conference Proceedings, 2016, 225-231.

[23] V.N. Khmelev, A.V. Shalunov, R.N. Golykh, K.V. Shalunova, A.N. Galakhov and V.A. Nesterov, Revealing of optimum modes of ultrasonic coagulation of subμm 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, 2014, 208-212.

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

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

[26] V.N. Khmelev, A.V. Shalunov, R.S. Dorovskikh, R.N. Golykh 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 of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2016: Conference Proceedings, 2016, 246-250.

[27] C.D. Sheng and X.L. Shen, Modelling Acoustic Agglomeration Processes Using Direct Simulation Monte Carlo Method, Journal of Aerosol Science, 2006, 16–36.

[28] W. Xie, R. Li and X. Lu, Pulsed ultrasound assisted dehydration of waste oil, Ultrason Sonochem, 2015, 136-141.

*V.N. Khmelev " The Formation of High-Dispersed Liquid-Drop Systems in the High-Intensity Ultrasonic Fields." American Journal of Engineering Research (AJER) 6.8 (2017): 184-194