Evaluation of The Area of Intensive Coagulation of Dispersed-Phase Particles In Emulsion And Suspension Due To High-Intensive Ultrasonic Treatment

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***Abstract* – the article is devoted to studying of intensification of stable emulsions and suspensions separation process under the action of ultrasonic treatment.**

***Index Terms* – Ultrasound, ultrasonic intensification of emulsion and suspension separation process, coagulation, disjoining pressure.**

I. INTRODUCTION

THERE ARE MANY technologies producing harmful substances in solid and liquid form have place in chemical, petrochemical, mining, oil and gas, food and agriculture industries. Range of materials and sizes of polluting particles is pretty wide. Separating of large particles goes easily but nanoscale particles coagulation is very difficult (stable emulsions and suspensions).

Also, together with waste control problem there is a need for fast and predictable separation of stable emulsions and suspensions formed in different technological processes of chemical industry.

One of high-effective approach to solving the problem of increase of efficiency of chemical industry processes and decrease of its environmental impact is using of ultrasonic vibrations of various intensity.

In high intensive ultrasonic treatment of liquid media the collapsing cavitation bubbles provide acceleration of extraction, emulsification, dispersion and similar processes in hundred and thousand times.

Processes passed during spreading of low intensity ultrasonic vibrations in liquid media are less studied. In such case, arising and periodically changing areas of compression and rarefaction generate the forces assisting to approach, consolidation and sedimentation of solid particles, chemical compounds and biological substances saturating a solution. Unfortunately, practical realization of such processes isn't used widely in industry due to complication of selecting of optimal conditions treatment and absence of specialized equipment for ultrasonic treatment excluding destructive action of cavitation.

II. PROBLEM DEFINITION

Thereby problem of making specialized ultrasonic equipment for increase in efficiency of emulsions and suspensions destabilization through ultrasonic treatment is actual.

III. THEORY

At analyze of stable emulsions and suspensions in colloid stability theory it is studied the disjoining pressure including molecular $\Pi_m(h)$, electrostatic $\Pi_e(h)$ and structural $\Pi_s(h)$ components. Potential energy U_e of electrostatic repulsion can be evaluated:

$$U_e = \frac{64RTc_\infty}{\kappa}\gamma^2 e^{-2\kappa x} \qquad (1)$$

where R – universal gas constant value; T – absolute temperature value; $\gamma = \frac{exp(zF\varphi_0/2RT)-1}{exp(zF\varphi_0/2RT)+1}$ – parameter depending on particle charge φ_0; $\kappa = \sqrt{\frac{2(zF)^2 c_\infty}{\varepsilon\varepsilon_0 RT}}$ – inverse value of thickness of electrical double layer (EDL); c_∞ – concentration of electrolyte in solution; x – space between particles.

Attraction between particles can be expressed as:

$$U_m = -\frac{\pi n^2\beta}{12}\frac{1}{(2x)^2} = \frac{A}{48x^2} \qquad (2)$$

where $A = \pi n^2\beta$ – Hamaker constant value; x – space between particles [1].

Considering equilibrium condition the space between particles x_{min} is expressed as change of first derivative sign $\frac{dU_{total}}{dx} = 0$ from negative to positive value. In such way space between particles appropriative to maximum of total energy of particles interaction x_{max} is expressed as:

$$\frac{dU_{total}}{dx} = 64RTc_\infty\gamma^2 e^{-2\kappa x} - \frac{A}{48\pi x^3} = 0 \qquad (3)$$

$$64RTc_\infty\gamma^2 e^{-2\kappa x} = \frac{A}{48\pi x^3}. \qquad (4)$$

Work of acoustic field forces in travelling-wave for moving one particle to another particle at distance x_{min} taking into account $I = \frac{\rho_ж v_0^2}{2}c$ is expressed as:

$$A_{US} = \frac{2}{9}\frac{\pi R^2(kR)^4 I}{c}\left(a_1^2 + a_1 a_2 + \frac{3}{4}a_2^2\right)x_{min} \qquad (5)$$

where R – particle radius value; k – wavenumber value; I – ultrasonic treatment intensity value; $a_1 = 1 - \frac{c^2\rho_ж}{c_т^2\rho_т}$; $a_2 = 2\frac{(\rho_т-\rho_ж)}{2\rho_т+\rho_ж}$; $c_т$ – value of speed of ultrasonic spreading in particle material; $\rho_ж$ – value of density of liquid phase; $\rho_т$ – particles material density value.

At spreading of ultrasonic vibrations in real liquid medium it is necessary to consider energy losses.

In a flat wave while spreading in medium the intensity decreases as:

$$I = I_0 e^{-2\frac{\beta}{c}x} = I_0 e^{-2\delta x} \qquad (6)$$

where $\delta = \frac{1}{2c\xi}\frac{d\xi}{dt}$ – absorption coefficient; x – distance from ultrasonic radiator.

Together with wave absorption in real liquid media it has place the dissipation of wave energy on dispersed particles:

$$I_{dis} = I_0 \frac{k^4 R^6}{9r^2}\left(1 + \frac{3}{2}\cos\theta\right)^2 \qquad (7)$$

where I_0 – value of intensity of ultrasonic vibrations near radiator; k – wavenumber value; R – particles radius value; r – distance from ultrasonic radiator.

For studying of ultrasonic field changing along radiator axis the formula of intensity can be expressed as:

$$I_{dis} = I_0 \frac{25k^4 R^6}{36r^2}. \qquad (8)$$

Total intensity of depressed ultrasonic wave:

$$I_{dep} = I_0\left(1 - \frac{25k^4R^6}{36x^2}\right)e^{-2\delta x} \qquad (9)$$

where x – distance from ultrasonic radiator; δ – absorption coefficient.

Except of energy dissipation it is necessary to evaluate waste of energy due to cavitation.

Work of hydrostatic and acoustic pressures for expansion of total count cavitational bubbles is expressed as:

$$A_{cav} \cong P\Delta V \qquad (10)$$

where P – value of hydrostatic and acoustic pressures sum; ΔV – total gain of bubbles volume value.

The pressure can be expressed as:

$$P = \rho_l gh + \frac{2I}{c} \qquad (11)$$

where g – gravitational constant value; h – radiator depth value; I – ultrasonic treatment intensity value; c – speed of ultrasonic vibration spreading in liquid media.

Total volume of cavitational bubbles can be evaluated understanding the equality to 0.7 of cavitation index value in "developed-cavitation" mode.

Size of cavitation field x_k depending of ultrasonic treatment intensity can be evaluated as:

$$x_k = 2{,}5\rho_к c_к K p_к^{\frac{5}{2}}\left(1 - \left(\frac{I_{thr}}{I_0}\right)^{\frac{5}{4}}\right) \qquad (12)$$

where $I_{опт}$ – threshold value of ultrasonic intensity for realization of "developed-cavitaion" mode, $\rho_к c_к$ - wave resistance of cavitating fluid, K – constant value, $p_к$ - value of ultrasonic wave pressure causing cavitation of liquid medium, I_0 – value of ultrasonic field intensity near radiator.

Expressing the cavitation area volume through Fresnel and Fraunhofer equations it can be evaluated the size of area of particles coagulating intensification under influence of acoustic field energy.

On the base of (1), (2), (5) and (14) equations it can be noted:

$$A_{US} - A_{cav} = U_e - U_m \qquad (13)$$

Left part of this equation corresponds to energy of acoustic field and right part – to energy of forces of interaction between particles in liquid medium. Using a substitution $I_{dep} = I_0\left(1 - \frac{25k^4R^6}{36x^2}\right)e^{-2\delta x}$:

$$\frac{2}{9}\frac{\pi R^2 (kR)^4 I_0\left(1 - \frac{25k^4R^6}{36x^2}\right)e^{-2\delta x}}{c}\left(a_1^2 + a_1 a_2 + \frac{3}{4}a_2^2\right)x_{min} -$$

$$-0{,}7\pi\left(\rho_l gh + \frac{2I_0\left(1 - \frac{25k^4R^6}{36x^2}\right)e^{-2\delta x}}{c}\right)\left(R_{rad}^4/\Lambda + \frac{1}{3}(x_k - R_{изл}^2/\Lambda) \times\right.$$

$$\times\left(R_{rad}^2 + 0{,}61\Lambda\left(R_{rad}\left(1 - \left(\frac{0{,}61\Lambda}{R_{rad}}\right)^2\right)^{\frac{1}{2}}\right)^{-1}(x_k - R_{rad}^2/\Lambda) + R_{rad}\right)^2 +$$

$$\left. + 0{,}61\Lambda R_{rad}\left(R_{rad}\left(1 - \left(\frac{0{,}61\Lambda}{R_{rad}}\right)^2\right)^{\frac{1}{2}}\right)^{-1}(x_k - R_{rad}^2/\Lambda) + R_{rad}\right)\Bigg) =$$

$$= \frac{64 R_g T c_\infty}{\kappa}\gamma^2 e^{-2\kappa x_{max}} - \frac{A}{48 x_{max}^2} \qquad (14)$$

where Λ – ultrasonic wavelength value; x_{min} – value of space between articles corresponding to minimum of total energy of interaction; x_k – size of cavitation area; R_g – universal gas constant value; x_{max} – value of space between particles corresponding to maximum of total energy of interaction.

Obtained equation can be expressed in graphic evaluation method. Result provides information about size of area in treated liquid medium with conditions useful for coagulation.

IV. EXPERIMENTAL RESULTS

An evaluations for various stable emulsions and suspensions give the information about ultrasonic coagulation area depending on frequency and intensity of ultrasonic treatment. The size of area is changed from cavitational area (3-10 R_{rad}) to distance about 100-1000 R_{rad}. For example if radiator radius equals to $20 \cdot 10^{-3}$ m and ultrasonic frequency - $22 \cdot 10^3$ Hz the size of coagulation area changes from $35 \cdot 10^{-2}$ m to 18 m with various intensity of ultrasonic treatment.

V. DISCUSSION OF RESULTS

Reviewed possible cases of ultrasonic treatment using for realization of coagulation process confirm the fact of impossibility effective and predictive separating of dispersed phase particles in emulsions and suspensions. For providing the conditions of intensifying of coagulation and reducing of dispersion there is a need to design specialized equipment. For that it is necessary to realize specific engineering and design solutions for exception destructive cavitation and for intensifying of coagulation.

A. *Decreasing of Ultrasonic Treatment Intensity*

Decreasing of ultrasonic vibrations intensity is one of ways to suppress cavitational processes activity arising in spreading of ultrasonic vibrations in liquid medium. If energy of vibrations spreading in liquid medium is small, it doesn't occur significant expand of steam-gas bubbles. In this case all injected energy can be spent to increasing size of dispersed phase particles in treating emulsion or suspension. However because of small ultrasonic vibrations intensity it takes place damping near of radiator but coagulation activity in the distance absents at all (see Fig. 1).

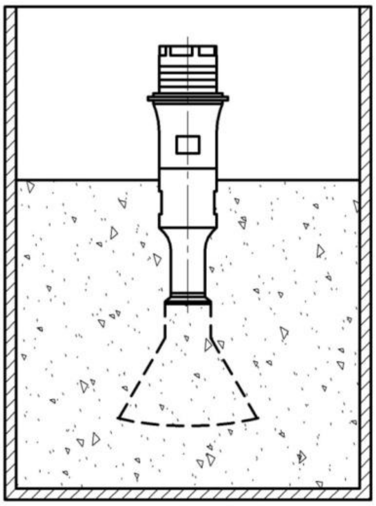

Fig. 1. Location of area of dispersed phase particles coagulation at low intensity of ultrasonic treatment

Because of it, the ultrasonic equipment with low intensity of radiating vibrations can be used for intensifying of separation of emulsions and suspensions in small-scale tanks with considerable length of treatment.

B. *Making of Excessive Pressure in Treated Liquid Medium*

For significant decreasing of cavitational processes activity it is possible to make the excessive pressure in treated emulsion or suspension. In this case at substantial energy of ultrasonic frequency vibrations it doesn't occur of active formation and destruction of steam-gas bubbles because of insufficient pressing force of injecting vibrations. Level of required excessive pressure is individual for each components combination in treated emulsion or suspension and ultrasonic treatment intensity.

Mechanical vibrations spreading in treating emulsion or suspension will assist in coagulation of small dispersed phase particles on significant distance from radiator. In this case the destruction of formed agglomerates is unlikely (see Fig. 2).

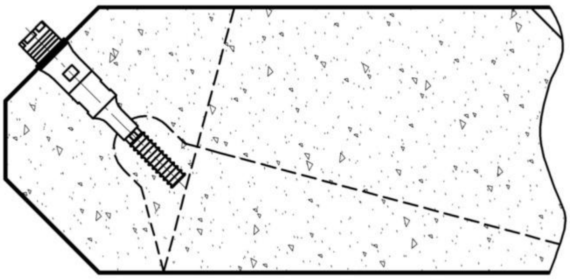

Fig. 2. Location of area of dispersed phase particles coagulation at low intensity of ultrasonic treatment

Realization of ultrasonic treatment of emulsions and suspensions at excessive pressure requires of specific energy costs. However, it arise the possibility of increasing of treated tank and treated speed and in some cases the possibility of flowing treating.

Unfortunately, the realization of such conditions at treating of big tanks in industry is difficult.

C. *Displacing of Dispersed Particles Out of Intensive Cavitational Activity Area*

It should be noted the formation of cavitation also can be used for coagulation of dispersed phase particles in emulsion or suspension. For significant dispersed-phase particles coagulation it is necessary to use mechanical vibrations of different frequencies. At collapsing of cavitational bubbles in liquid area it occur mechanical vibrations of different intensity with frequency from hundreds of hertz to dozens of megahertz.

Except of described arrangements of cavitation preventing it has place the possibility of substantial decreasing probability (prior to it exception) of passing of dispersed-phase particles in destructive cavitational area. For that it is necessary to make specific treatment in treated tank for removing of dispersed phase out of active cavitational area near of radiator.

For carrying out of such treatment it's necessary to organize the sonification in cylindrical tank with intensive circular moving forming due to injection of treating emulsion or suspension tangentially with high speed of flow. Herewith it's necessary to locate the ultrasonic radiator axisymmetrically in the center of tank. In fast-moving around a circle medium it will occur the displacement of dispersed phase particles under action of centrifugal force (if their density more than dispersion medium density) and by that particles will leave a destructive cavitational area (see Fig. 3).

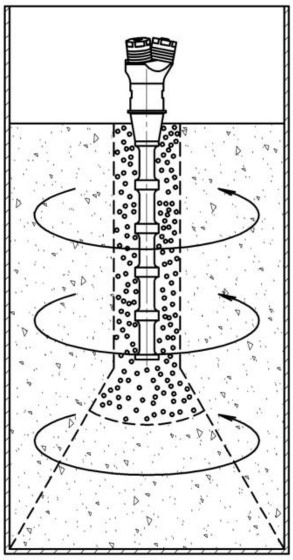

Fig. 3. Displacement of dispersed particles out of high cavitational activity area under action of centrifugal force

Moreover, together with boosting of dispersed phase particles coagulation under the action of broadband mechanical vibrations it will be coagulation under the action of centrifugal force.

Described method of intensification of emulsions and suspensions separation has some limitations. It can be used only in case of more heavy dispersed phase particles toward dispersion medium and in case of high speed of flow. Herein it is important to provide maximum possible intensity of injecting vibrations.

D. *Isolating of Cavitational Area*

For realization of boosting of coagulation processes in various emulsions and suspensions with considering the shortcomings of described methods it is necessary to isolate dispersed phase components from entering into destructive cavitational area and to provide high energy and broadband of ultrasonic treating. For meeting of described conditions it’s necessary to separate intensive coagulation area from sonificating tank by the closed sound-conducting container for preventing of destruction of agglomerated dispersed-phase particles in intensive cavitation area (see Fig. 4).

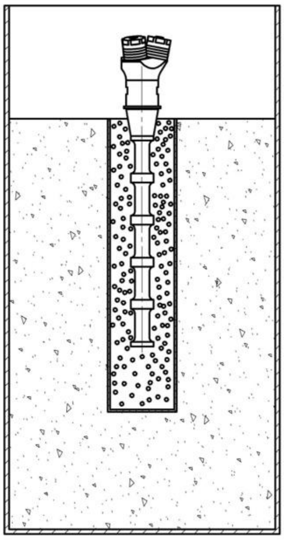

Fig. 4. Isolating of intensive cavitational area from sonificating tank by the closed sound-conducting container

For properly working of sound-conducting container it can be pretty hard (in acoustic meaning). If rigidity of sound-conducting container is insufficient the falling waves excite bending type and other vibrations. As a result the standing waves occur on the surface of container. It means the all point of sound-conducting container has specific amplitude and phase of vibrations. Existence of such additive vibration source can reduce basic radiation in a few times. So at designing of sound-conducting container it’s necessary to consider the possibility of standing wave arising and for this it’s necessary to select the correct thickness of container. Particularly for usually used frequency range of ultrasonic vibrations the thickness of container can be at least $4 - 5 \cdot 10^{-3}$ m [4].

It should be noted, mechanical vibrations of sound-conducting container wall are the sum of vibrations of ultrasonic radiator basic frequency and vibrations of broadband spectrum formed as a result of cavitational collapsing of many steam-gas bubbles. Summed wave composition passes into external treating medium. As a result, destructive cavitational processes has place only inside sound-conducting container and outside small particles of dispersed phase coagulate due to structuring in ultrasonic wave and agglomerating due to vibrations of broadband spectrum.

In this case as described in previous method it is necessary to use ultrasonic radiators with maximum intensity of vibrations injecting in medium.

VI. Conclusion

Basing on the results of theoretical researches of dispersed-phase particles coagulation process in emulsions and suspensions it can be offer methodical and constructive solutions for applying of ultrasonic technological equipment in existing chemical equipment and for making of specialized equipment for intensifying of stable emulsions and suspensions separation process.

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