Study of Interaction of Cavitation Zone With Interphase Boundary For the Determination of Efficient Modes of Ultrasonic Intensification of Physical-chemical Processes

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Abstract **– The article describes the model of the interaction of cavitation zone formed under the action of ultrasonic vibrations and interphase boundary of gas and liquid media, which spreads on solid surface in the form of liquid layer. It is shown that this interaction leads to the generation of capillary waves and consequently to the increase of efficiency of physical-chemical processes due to enlarged "liquid-gas" boundary. The analysis of the model allows determining square of interphase surface in dependence on amplitude, frequency of ultrasonic oscillations and liquid properties. It allows to determine the modes of ultrasonic action, which is necessary for maximum increase of contact surface area, in turn it leads to the growth of speed of the realization of physical-chemical processes based on surface interaction of dissimilar substances. As a result of the analysis it was determined that the most appropriate frequency of ultrasonic action is 60 kHz, at which increase of contact surface from 200 to 780 m^2/m^3 (at 5 mm thickness of liquid film) can be achieved.**

Index Terms **– Ultrasound, cavitation, interphase boundary, capillary waves, absorption.**

I. INTRODUCTION

THE SPEED OF the realization of the most part of physical-chemical processes is limited by boundary surface of interacting substances or phases and also by the speed of entering of reagents to this interface. Most of these processes occur in two-phase systems "liquid-gas".

For instance, in the systems "liquid-gas" gas wet cleaning from dispersed admixtures; absorption of gaseous mixtures as for their cleaning and for extraction of target components; drying of the materials are carried out.

It is evident, that for maximum efficiency of the processes first of all it is necessary to provide the large contact area of liquid and gas phases.

One of the promising methods of the increase of the interface is the action of microscopic shocking waves leading to the generation of profile agitation of the interface "liquid-gas" (capillary waves). The occurrence of shock waves can be provided due to the generation of periodically expanding and collapsing cavitation bubbles in liquid phase. It is known, that the most energy profitable method [1,2] of cavitation bubbles generation is the introduction of ultrasonic vibrations into liquid phase with the ultrasonic frequency (more than 20 kHz) by the solid-state radiator.

That is why it is necessary to develop the model, which allows reveal optimum modes of ultrasonic action providing maximum area of the interphase boundary "liquid-gas".

There is no doubt, that large specific interface area (per unit volume of liquid phase) required for industrial realization of physical-chemical processes at the interphase boundary can be provided in the case, when liquid spreads on the surface of the solid in the form of thin layer (for instance, in film and packed absorbers, where the thickness of the layer does not exceed 5 mm).

Solid surface reflecting microscopic shock waves will essentially influence on the generation of cavitation bubbles in liquid phase under the action of ultrasonic vibrations. It leads to the fact, that the bubbles will collapse asymmetrically [3]. While the most part of theoretical studies devoted to the formation of cavitation bubbles in liquid phase is based on the assumption of spherical symmetry of the bubble during the cycle of expansion and collapse [1,2,4].

Stated factor should be taken into consideration at the studies of the cavitation bubble generation in thin layer of liquid.

Further we describe proposed model of the interaction of cavitation bubbles with the interface "liquid-gas" taking into account asymmetry of their collapse and allowing determine the modes of ultrasonic action, which are necessary for the achievement of maximum interface.

II. MAIN PART

The model presented in the article includes step-by-step consideration of the following stages of capillary waves generation on the interphase boundary "liquid-gas" under the action of ultrasonic cavitation:

– *expansion of the cavitation bubble* to maximum radius, which is spherically symmetric due to the low radial velocity of the wall motion;

– *asymmetric collapse of the cavitation bubble* from maximum radius to minimum sizes;

– *generation and propagation of focused shock wave* in the thin layer of liquid at the collapse of the cavitation bubble;

– *formation of capillary wave* on the interphase boundary "liquid-gas".

Theoretical study of examined process is carried out according to the scheme shown in Fig. 1.

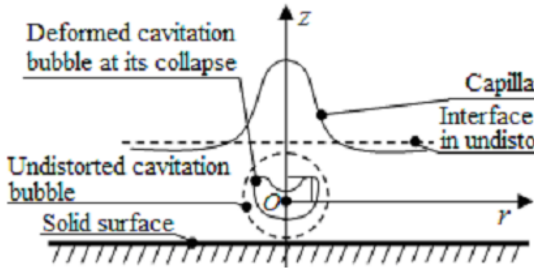


Fig. 1. Example of figure design.

While studying the stage of cavitation bubble expansion its maximum radius R_{MAX} depending on frequency, vibration amplitude of the solid surface and physical properties of liquid is determined.

The maximum radius of the cavitation bubble is defined on the base of the Nolting-Nepayres equation [3]:

$$\rho\left(\frac{3}{2}\left(\frac{\partial R}{\partial t}\right)^2 + R\frac{\partial^2 R}{\partial t^2}\right) = p_V - p_0 + 4\pi^2 f^2 \rho A h \sin(2\pi f t) - 4\mu\frac{\frac{\partial R}{\partial t}}{R} + \left(p_0 + \frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma};$$

where R is the instantaneous radius of the cavitation bubble, m; R_0 is the radius of the cavitation nucleus, m; σ is the surface tension of liquid, N/m; ρ is the density of liquid, kg/m^3; p_0 is the static pressure in liquid, Pa; f is the frequency of ultrasonic action, Hz; h is the thickness of liquid layer, m; A is the amplitude of the ultrasonic action, m; p_V is the saturated vapor pressure of liquid interacting with gaseous, Pa.

At the consideration of the stage of cavitation bubble collapse we define its form at the moment of the achievement of minimum sizes on the base of the integral equation (1) with boundary condition (2) for liquid velocity potential surrounding cavitation bubble:

$$\frac{\varphi(\mathbf{r}_0)}{2} = \int_{S_A \cup S_B} \left(E_{\mathbf{r}_0}(\nabla\varphi, \mathbf{n}) - (\nabla E_{\mathbf{r}_0}, \mathbf{n})\varphi\right)\partial S; \qquad (1)$$

$$\frac{\partial\varphi}{\partial t} + \frac{|\nabla\varphi|^2}{2} = \frac{2\sigma K}{\rho} - \frac{p_V}{\rho}\left(\frac{3V}{4\pi R_{MAX}^{3}}\right)^{\gamma}; \qquad (2)$$

where $\mathbf{r}_0$, $\mathbf{r}$ are the vectors of position of the points of the cavitation bubble wall or solid surface, m; φ is the velocity potential of liquid motion on the wall of the cavitation bubble or solid surface, m^2/s; $\mathbf{n}$ is normal vector to the cavitation bubble wall; $E_{r_0}(\mathbf{r})$ is the fundamental solution of Laplace equation; V is the volume of the cavitation bubble, m^3; p_V is the liquid saturation vapor pressure, Pa; ρ and σ are the density (kg/m^3) and surface tension of liquid (N/m), respectively; K is the average curvature of the cavitation bubble walls, m^{-1}; S_A is the wall of the cavitation bubble, at which integration takes place; S_B is the solid surface.

Obtained forms of the cavitation bubble walls at the collapse in different moments of time are shown in Fig. 2. The moment, when the bubble achieves maximum expansion, is taken as an initial moment of time (0 µs).

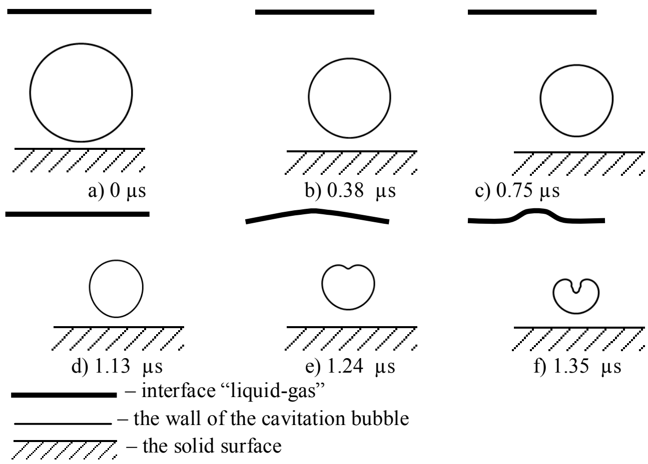


Fig. 2. Development of the form of asymmetrically collapsing cavitation bubble in the course of time.

As it is evident from Fig. 2f, the cavitation bubble represents semispheric radiator of the shock wave.

At the study of the stage of the generation and propagation of shock wave it allows approximate the profile of its pressure near the interface "liquid-gas" by the following obtained expression (3):

$$p(\mathbf{r},t) = \frac{\omega}{2\pi}\sum_{n=-\infty}^{\infty} e^{-in\omega t}\int_S iG_{\mathbf{r}_0, n\frac{\omega}{c}+\frac{i\eta n^2\omega^2}{2\rho c^3}}(\mathbf{r})\frac{n\omega}{c}\int_0^{\frac{2\pi}{\omega}} p_c(t_1)e^{in\omega t_1}\partial t_1 \partial S_0 \qquad (3)$$

where $\mathbf{r}=(x;y;z)$ are the coordinates of the point of the interphase boundary "liquid-gas", m; ω is the angular vibration frequency of the solid surface, s^{-1}; t and t_1 are the moments of time, s; η is the viscosity of liquid phase, Pa·s; ρ and c are the density and the velocity of sound of the liquid phase, respectively, m/s; $p_c(t_1)$ is the pressure in the nucleus of the cavitation bubble, Pa; a is the radius of the cavitation bubble at the achievement of maximum pressure in its nucleus, m; $G_{\mathbf{r}_0, n\frac{\omega}{c}+\frac{i\eta n^2\omega^2}{2\rho c^3}}$ is the Green's function [5] at wave number is $n\frac{\omega}{c}+\frac{i\eta n^2\omega^2}{2\rho c^3}$.

The function of the shock wave pressure in the nucleus of the cavitation bubble $p_c(t_1)$ being a part of the expression (3) is defined on the base of its obtained form in every moment of time according to the following ratio:

$$p_c(t_1) = p_V\left(\frac{2R_{MAX}^{3}}{\int_0^{\pi} r\left[z\frac{\partial r}{\partial\theta} - r\frac{\partial z}{\partial\theta}\right]\partial\theta}\right)^{\gamma};$$

where p_V is the saturation vapor pressure of liquid phase, Pa; $(r(\theta);z(\theta))$ are the coordinates of the points of the wall of the cavitation bubble (m) in the cylindrical system according to Fig. 1; R_{MAX} is the maximum radius of the bubble achieved at the stage of its expansion, m.

Obtained profile of the shock wave pressure is used further for the determination of the *form of the capillary wave* and finally the area of the interface.

For the profile of the capillary wave the expression (4) is valid:

$$\rho \frac{\partial^2 \xi}{\partial t^2}(r,t) = -\frac{\partial p}{\partial z}; \qquad (4)$$

where $\xi(r,t)$ is the value of the displacement of the interphase boundary "liquid-gas" on the axis z, m; $\frac{\partial p}{\partial z}$ is the gradient of pressure in the liquid on the interphase boundary, $Pa \cdot m^{-1}$.

Obtained profile of the capillary wave is used for the determination of the specific area of disturbed interface "liquid-gas" per unit volume of liquid on the base of the expression (5) taking into account coalescence and bubbles breaking [4]:

$$S = \frac{1}{h} + 4\pi f \left\langle \frac{j-1}{iS_{cc}U} \right\rangle \int_0^{0,5\lambda} r\sqrt{1+\left(\frac{\partial \xi}{\partial r}\right)^2}\,\partial r; \qquad (5)$$

where S is the specific area of the interface, m^2/m^3; λ is the length of the capillary wave (m) defined from the condition $\frac{\partial \xi}{\partial r}\left(\frac{\lambda}{2},t\right)=0$; f is the frequency of the ultrasonic action, Hz; S_{cc} is square of bubble collision cross section, m^2; U is the average approach velocity of the cavitation bubbles generated by Bjerknes force, m/sec; j is the number of the nucleus generated at the breaking of the single bubble; < > is the sign of averaging over the thickness of the liquid layer; h is the thickness of layer, m.

Thus, proposed model allows determine the dependences of square of the interface area (per unit of volume of liquid) on the modes of the ultrasonic action (frequency and vibration amplitude of the solid surface covered with liquid layer, which borders on gas phase) (see Fig. 3) and liquid properties (see Fig. 4).

In Fig. 3 the break of the graphs corresponds to the fact, that capillary wave loses its stability and it starts falling into drops. All the calculations are carried out at the thickness of liquid layer, which equals to 5 mm.

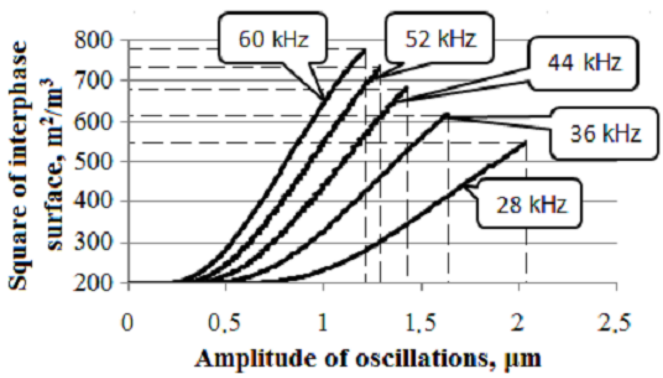
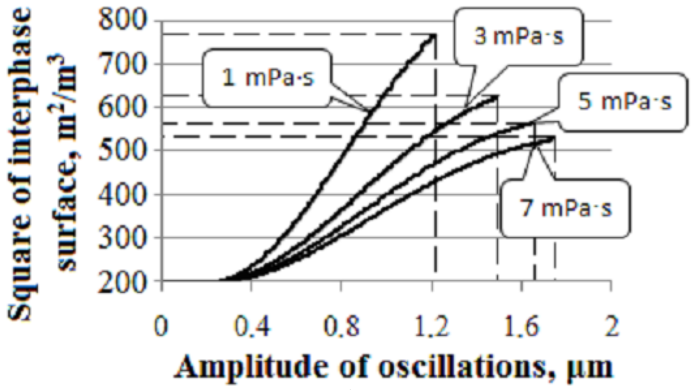
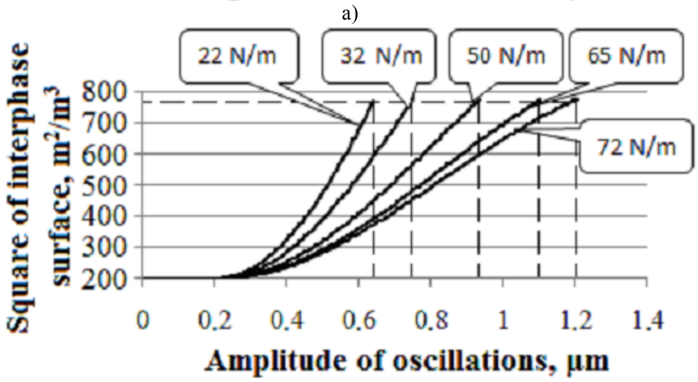


Fig. 3. Dependences of specific area of the interface on amplitude at different frequencies.

From presented dependences it is evident, that the area of the interphase boundary rises with the increase of the amplitude. If the frequency is increased, the interface area will grow due to the rise of the cavitation bubble concentration [1]. However, starting with the frequency of 60 kHz the growth of the area slows down, at the same time energy loss in the ultrasonic radiator rises quadratically. That is why the use of the frequencies of more than 60 kHz is unreasonable. Fig. 4 shows the dependences of square of the interphase boundary on amplitude at the changes of physical properties of liquid – viscosity (a) and surface tension (b), which essentially influence on the profile of contact face together with the modes of ultrasonic action.



a)



b)

Fig. 4. Dependences of a square of the interphase boundary area on amplitude at various liquid properties (frequency of 60 kHz).

Obtained dependences (see Fig. 4) can be applied for the determination of area change caused by the change of liquid type or its physical properties. In particular it is determined, that the growth of viscosity leads to the decrease of the specific interface area. It is caused by two factors:

– absorption of shock wave energy in liquid phase due to the viscous friction forces;

– viscous friction forces prevent from the expansion of the cavitation bubble.

At that decrease of the surface tension of liquid phase leads to the growth of the area, as there is a direct relation between the surface energy of a liquid and the surface tension.

III. CONCLUSION

Thus, we developed the model of the interaction of the cavitation zone generated under the action of ultrasonic vibrations with the boundary of gas and liquid phases. It was shown, that this interaction led to the formation of capillary waves and consequently to the increase of contact face.

The analysis of the model allowed determine the modes of ultrasonic action, which were necessary for maximum increase of interface area.

As a result of the analysis we determined the threshold amplitudes of solid surface vibrations covered with thin layer of liquid phase, which excess led to stability failure of capillary waves and their fall into liquid drops. It was shown, that the most appropriate frequency of ultrasonic vibrations was 60 kHz, at which almost 4-fold increase of the interface could be achieved (from 200 to 780 m^2/m^3).

Obtained new scientific results have both fundamental interest for the progress in understanding of physical mechanism of the interaction of cavitation bubbles in the interphase boundary "liquid-gas" and they can be used for the practical realization of physical-chemical processes on the boundary "liquid-gas" (absorption, drying, evaporation, etc.).

In particular the ultrasonic action in the packed absorbers lets use less than 3 heads without changes of absorption productivity.

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