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PROVIDING THE EFFICIENCY AND DISPERSION CHARACTERISTICS OF AEROSOLS IN ULTRASONIC ATOMIZATION

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This article is devoted to the investigation of the process of atomization of liquids under the action of ultrasonic vibrations. It has been shown that the ultrasonic atomization parameters are determined by the regimes of action (vibration frequency and amplitude of the atomization surface), the liquid properties (viscosity, surface tension), and the thickness of the liquid layer covering the atomization surface. To reveal the dependences of the efficiency of the process at various dispersion characteristics of produced liquid droplets, we propose a model based on the cavitation-wave theory of droplet formation. The obtained results can be used in designing and using ultrasonic atomizers producing an aerosol with characteristics complying with the requirements on efficiency and dispersivity for the process being realized.

Keywords: *ultrasound, atomization, viscosity, aerosol, layer thickness, capillary wave.*

Introduction. Imposing mechanical vibrations of ultrasonic (US) frequency on a thin liquid film causes the formation on its surface of a network of capillary waves, from whose crests liquid droplets can detach themselves. This process is called ultrasonic atomization. The chief advantages of ultrasonic atomization are high dispersivity, small spread in values of droplet sizes with respect to the mean value, low energy consumption, and no need for a scattering agent. Due to this, ultrasonic atomization finds wide application in realizing various technological processes connected, for example, with spray drying [1], spraying on coatings (e.g., a photoresist on the surface of silicon plates, a flux on printed-circuit boards, anticoagulants on medical articles, etc.) [2–5], microcapsulation of medicinal substances [2, 5], spraying inhibitors on coronary stents [6], and obtaining nanopowders [7]. The dispersion characteristics of the formed aerosol, at which the maximum efficiency of the process is attained, and the required thickness and homogeneity of coatings will be unique for each process being realized.

It is known [8] that in ultrasonic atomization the efficiency of the process and the dispersion characteristics of produced liquid droplets depend on the regimes (vibration frequency and amplitude of the atomization surface), the properties of the liquid (viscosity, surface tension), as well as the thickness of the liquid layer covering the atomization surface. The existence of such dependences permits controlling the droplet size and the efficiency of atomization by varying the vibration frequency and amplitude.

However, providing the required efficiency of atomization of liquids differing in physical properties at a given dispersivity of particles makes it necessary to form a liquid layer of certain thickness and maintain the necessary amplitude and frequency of ultrasonic vibrations. That the given problem is topical is evidenced by the considerable number of publications devoted to the establishment of dependences of dispersion characteristics of produced droplets on the regimes of ultrasonic action. Unfortunately, most of these publications are devoted to the investigation of the specific case of high-dispersion atomization in a fountain (at frequencies higher than 1 MHz) [9–12]. Examples of dependences obtained experimentally are given in the publications of groups of researchers of the Nagoya University (Japan) [10], the Harvey Mudd College (California) [11], and the Salerno University (Italy) [12]. However, the above method of atomization is characterized by a very low efficiency (no more than 0.01 ml/s), which limits the possibilities of its practical application.

For the method of low-frequency US atomization in a layer (at frequencies of 20–250 Hz [2, 5, 13], experimental investigation were carried out under T. Asami′s supervision (Japan) [14] with the aim to determine the empirical dependences of the dispersion composition of produced aerosol on the physical properties of liquids. The theoretical studies are restricted thereby to general approaches and models for describing the process [13, 15–17] that do not allow determination of the

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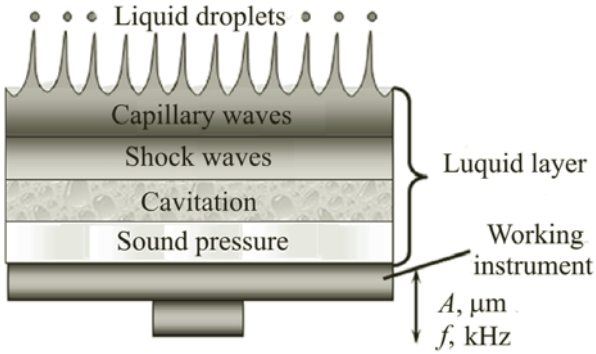

Fig. 1. Schematical representation of the cavitation mechanism of droplet production in the atomized liquid layer.

atomization efficiency and the diameter of produced droplets depending on the liquid properties and the regimes of US action.

Since the efficiency of the process at given dispersion characteristics is the basic characteristic of ultrasonic atomization, the establishment of functional dependences between the efficiency of atomization of liquids differing in properties at given characteristics of produced droplets and the regimes of ultrasonic action will open up new possibilities of using it to solve effectively problems of spraying on coats and realizing chemical-technological processes in disperse systems with a carrying gas phase [18–23].

Physical Processes Proceeding in Ultrasonic Atomization of a Liquid in a Thin Layer. At present the atomization efficiency is defined as [13]

$$\Pi = VfN_s \ . \tag{1}$$

In turn, to determine the diameter of produced droplets depending on the frequency of ultrasonic action, the expression obtained by R. J. Lang [24]

$$d_p = 0.34 \left(\frac{8\pi\sigma}{\rho f^2} \right)^{1/3} \tag{2}$$

is used. However, the above expressions are applicable only in the cases where the viscosity and thickness of the liquid layer and the amplitude of ultrasonic action have no influence on the process of atomization. At the same time it has been proved experimentally that the above parameters strongly influence the droplet diameters and the atomization efficiency [6, 10]. The expressions (1) and (2) corrected by introducing correction factors [12, 24, 25] obtained empirically hold only for certain classes of liquids and in many cases have no physical meaning since they do not permit explaining the mechanism of influence of physical properties of liquids on the atomization efficiency and sizes of produced droplets.

Thus, at present there is no scientifically substantiated mathematical apparatus that would permit establishing functional dependences between the atomization efficiency, the characteristics of produced droplets, and the regimes of ultrasonic action taking into account the physical properties of atomized liquids. To solve this problem, it is necessary to consider sequentially the processes proceeding in the atomized liquid layer with account for the influence of the physical properties of the liquid and the regimes of ultrasonic action on them.

Of the theoretically possible mechanisms of US atomization of liquids [24, 26, 27], the cavitation-wave mechanism has received the most study and has been verified experimentally. According to this mechanism, capillary waves are formed on the liquid film surface by collapse of cavitation bubbles (Fig. 1). Energetically, it is clear that the energy of US vibrations set up by the radiating (vibrating) surface undergoes a series of transformations. First the energy of the initial action (ultrasonic vibrations) is concentrated into a high-density energy in the form of periodic high-amplitude shock waves of collapsing cavitation bubbles. Then the energy of shock waves, propagating throughout the liquid layer thickness, reaches the free "liquid–gas" surface, changing into surface energy of capillary waves and increasing the free surface of the liquid due to the detachment of droplets from the crests of capillary waves.

The model proposed for further investigations incorporates all stages of energy transformation in the atomized liquid layer, namely

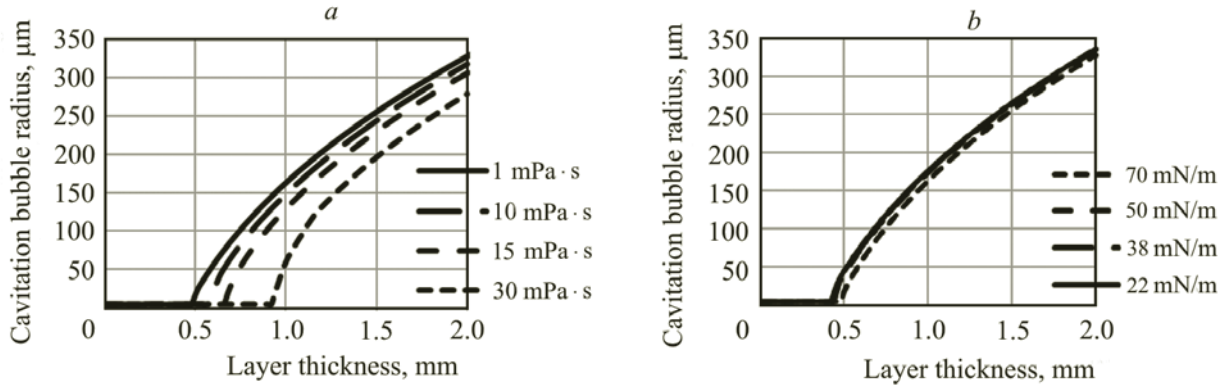

Fig. 2. Maximum radius of the cavitation bubble versus the liquid layer thickness at various viscosities (a) and surface tensions (b).

1) analysis of the cavitation development in the atomized liquid layer;
2) determination of the capillary wave profile;
3) determination of the atomization efficiency and the diameter of produced droplets depending on the wave profile.

These three stages of analysis of the proposed model are described in more detail below.

Analysis of the Cavitation Development in the Atomized Liquid Layer. Since in the liquid layer the sound pressure reaches the highest value near the vibrating surface [2, 13], of practical interest is the formation of cavitation bubbles in the layer abutting on the surface of the ultrasonic radiator. Therefore, the Kirkwood–Bethe equation describing the vibrations of the cavitation bubble walls and refined for the case of cavitation development in a thin liquid layer is used for analysis:

$$R\left(1-\frac{1}{C}\frac{\partial R}{\partial t}\right)\frac{\partial^2 R}{\partial t^2}+\frac{3}{2}\left(1-\frac{1}{3C}\frac{\partial R}{\partial t}\right)\left(\frac{\partial R}{\partial t}\right)^2=\left(1+\frac{1}{C}\frac{\partial R}{\partial t}\right)H+\frac{R}{C}\left(1-\frac{1}{C}\frac{\partial R}{\partial t}\right)\frac{\partial H}{\partial t},$$

$$H=\frac{n}{n-1}\frac{(p_0+B)^{\frac{1}{n}}}{\rho_0}\left[(p_0-\rho_0\omega^2 Ah\sin(\omega t)+B)^{\frac{n-1}{n}}-\left(p_{g0}\left(\frac{R_0}{R}\right)^{3\gamma}-\frac{2\sigma}{R}-\frac{4\mu}{R}\frac{\partial R}{\partial t}+P_v+B\right)^{\frac{n-1}{n}}\right], \quad (3)$$

where C is the local velocity of sound in the liquid, m/s; H is the liquid enthalpy, m^2/s^2; R is the bubble radius, m; n is a constant equal to 7; B is a constant equal to 3000 Pa; p_0 is the equilibrium pressure of the liquid, Pa; p_{g0} is the equilibrium pressure of the gas, Pa; R_0 is the cavitation nucleus radius, m; μ is the dynamic viscosity, mPa·s; P_v is the pressure of saturated vapors, Pa; t is the time from the beginning of action, s; σ is the surface tension coefficient, J/m^2; γ is the adiabatic index for air. The obtained expression relates the amplitude and frequency of action, the thickness of the atomized liquid, and the viscosity and surface tension of the liquid, i.e., all basic parameters determining the atomization efficiency and the dispersion characteristics of produced liquid droplets. The dependences of the maximum radius of cavitation bubbles on the liquid layer thickness at various vibration amplitude of the atomization surface (μm) are given in Fig. 2. As applied to the atomization process, the maximum radius of the cavitation bubble characterizes the stored energy that will subsequently be expended in forming a liquid droplet. From the dependences presented in Fig. 2 it follows that the cavitation bubble radius (i.e., the stored energy) is directly proportional to the vibration amplitudes of the atomization surface and increases with increasing thickness of the atomized liquid layer due to the increase in the sound pressure near the atomization surface.

Collapse of a cavitation bubble leads to the generation near the vibrating surface of a shock wave propagating in the liquid later thickness. This phenomenon is analogous to the phenomenon of underwater explosion in the depth of sea water. Therefore, to determine the pressure amplitude of the shock wave in the front when the wave reaches the free surface of the liquid, the transformed expression obtained by R. Cole [28] as a result of investigations of the underwater explosion (4) is used:

$$P_{\max}=\frac{\rho_0 c^2}{\sqrt{2}}\sqrt{\theta\frac{cP_1R_{\min}}{B(n-1)}}\frac{1}{h\ln(h/R_{\min})}, \quad (4)$$

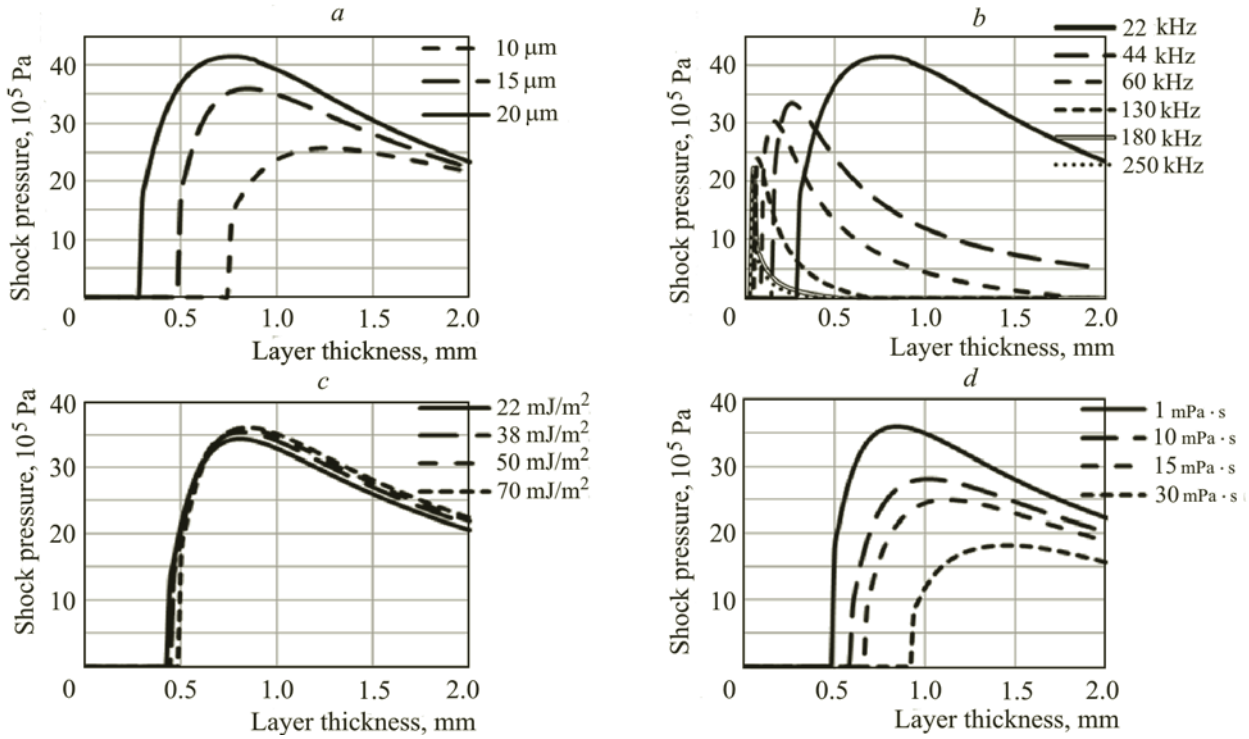

Fig. 3. Shock pressure versus the atomized liquid layer at various vibration amplitudes of the atomization surface (a), various vibration frequencies (b), various surface tensions (c), and various liquid viscosities (d).

where R_{min} is the minimum radius of the cavitation bubble by collapses which is determined on the basis of the Kirkwood–Bethe equation [28]. Using Eq. (4), we obtained a number of dependences of the shock pressure amplitude on the parameters of the US action, the layer thickness, and the properties of the liquid being atomized (Fig. 3). They permit establishing that in a wide range of regimes of US action and physical properties of the liquid being atomized there is always an optimum thickness at which the pressure amplitude of the shock wave will be minimum. The existence of the optimum thickness is due to the fact that at smaller thicknesses of the layer the drop of pressure is due to the decrease in the sound pressure amplitude in the liquid (4), and at large thicknesses it is due to the shock wave damping in the layer because of its scattering.

Since the pressure amplitude of the shock wave determines the energy imparted to the free surface and is used sequentially for the production of droplets, it may be assumed that at the optimum thickness the maximum atomization efficiency will also be attained [2]. An increase in the vibration amplitude or frequency leads thereby to a decrease in the optimum thickness of the liquid layer due to the fact that there is a decrease in the minimum size of the cavitation bubble, which is attained at the moment of its maximum compression by collapse. The generated shock wave is scattered faster thereby as it recedes from the center of the bubble.

For a similar reason, the optimum thickness of the layer increases with increasing viscosity or surface tension, since the forces of viscous friction or surface tension prevent the bubble from expanding. Consequently, its minimum size increases at maximum compression due to the decrease in the energy stored at the expansion stage. This leads to an increase in the optimum thickness of the layer due to the slower scattering of the shock wave.

The obtained curves of the shock pressure amplitude form the basis for further determination of the profile of generated waves.

Determination of the capillary wave profile. The profile of the capillary waves (Fig. 4) is evidently determined by the liquid flow near the "liquid–gas" interface from which droplets detach themselves. This flow is described by Navier–Stokes equations with capillary jump boundary conditions on the free surface [2, 17].

Since for capillary waves to be formed the amplitude of capillary waves should exceed the half-length of the latter, the free surface vibrations of the liquid will be strongly influenced by the nonlinear effects that are due to the convective transfer. To take these effects into account, we used a new approach to the solution of the Navier–Stokes equations based on

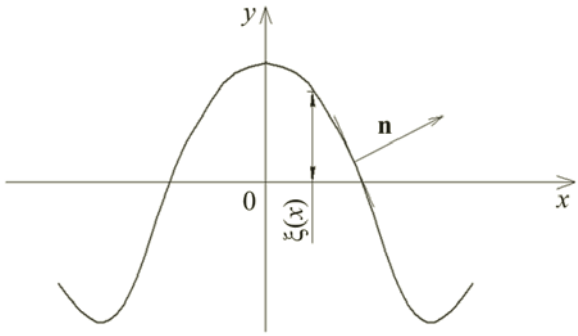

Fig. 4. Schematical representation of the capillary wave near the free "liquid–gas" surface (ξ is the free surface displacement, *n* is the normal vector to the free surface).

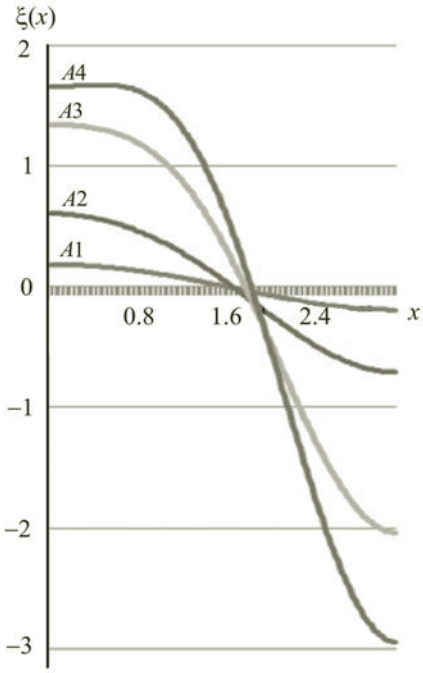

Fig. 5. Capillary wave profile at various amplitudes ($A4 > A3 > A2 > A1$) in relative units.

the asymptotic expansion of the vertical shift ξ of the free surface, the pressure p, and the velocity components of the medium ($u = u_x$, $v = u_y$) in the form of infinite sums from terms of various orders of nonlinearity:

$$\begin{aligned} \xi &= \sum_{n=1}^{\infty} \xi^{(n)} = \sum_{n=1}^{\infty} E^{(n)} A_{\max}^n \ , \quad p = \sum_{n=1}^{\infty} p^{(n)} = \sum_{n=1}^{\infty} P^{(n)} A_{\max}^n \ , \\ u &= \sum_{n=1}^{\infty} u^{(n)} = \sum_{n=1}^{\infty} U^{(n)} A_{\max}^n \ , \quad v = \sum_{n=1}^{\infty} v^{(n)} = \sum_{n=1}^{\infty} V^{(n)} A_{\max}^n \ , \end{aligned} \tag{5}$$

where the superscript (n) denotes the order of nonlinearity of the term (component) in the expansion of a quantity [2]. The above asymptotic expansions have made it possible to obtain, in the second approximation, the following expression for the capillary wave profile:

$$\xi(x, t) \approx A \sin(\omega t) \left(\cos(kx) - \left(\frac{Ak}{3} \cos(2kx) + 2Ak \right) \cos(\omega t) \right), \tag{6}$$

where $k = \frac{2\pi}{\lambda}$. The amplitude of the first-order wave component A (6) depends on the pressure amplitude of the shock wave according to the following expression obtained on the basis of the energy conservation law:

$$A = \frac{2P_{\max}\theta}{\rho\omega\lambda}\sqrt{\frac{c\theta}{\lambda\left(\frac{\pi^2}{4}-\frac{1}{8}\right)}}. \tag{7}$$

Figure 5 shows the capillary wave profile at various amplitudes A (in relative units). As follows from Fig. 5, at ultrasonic atomization in the regime of stable cavitation the capillary wave amplitude becomes comparable to its length (it exceeds the stability limit of the capillary wave — the amplitude exceeds 0.73 of its length [17]). This explains the production of droplets. The mean local displacement thickness of the liquid mass increases thereby with increasing amplitude, which permits explaining the experimentally observed dependence of the droplet diameter on the vibration amplitude of the atomization surface [2]. The obtained capillary wave profile forms the basis for determining the diameter of produced aerosol droplets. The dependences of atomization characteristics (atomization efficiency and droplet diameter) on the regimes of action and the properties of the liquid are given below.

Determination of the atomized liquid characteristics. *Determination of the diameter of produced droplets.* The droplet diameter is determined on the basis of the nonlinear capillary wave profile with the use of the Rayleigh theory of disintegration of jets, which holds true in view of the cylindrically symmetric form of the wave crest [2, 29, 30]:

$$D = 1.89D_{\text{avg}} = 3.78\frac{\int_0^{\frac{\lambda}{2}}\left(\xi(x)-\xi\left(\frac{\lambda}{2}\right)\right)\partial x}{\xi(0)-\xi\left(\frac{\lambda}{2}\right)}. \tag{8}$$

The dependences of diameters of produced droplets on the liquid properties and the amplitude of US action are given in Fig. 6. For each set of values of regimes of action and properties of the atomized liquid, hereinafter the optimum layer thickness is considered to be that at which the pressure amplitude of the shock wave is maximum (Fig. 3). From the presented dependences it follows that the diameter of produced droplets depends nonlinearly on the vibration amplitude of the atomization surface (Fig. 6a). For each investigated dependence there exists a certain vibration amplitude, the exceeding of which stops further increase in the diameter of produced droplets because of the limited average thickness of capillary waves D_{avg} of wavelength λ (6, 7). From the dependences presented in Fig. 6b it follows that as the viscosity is increased from 1 mPa·s (water viscosity) to the limiting value above which the atomization ceases (at a frequency of 22 kHz at 30 mPa·s, 44 kHz at 23 mPa·s, 60 kHz at 15 mPa·s, 130 kHz at 10 mPa·s, 180 kHz at 7 mPa·s, 250 kHz at 6 mPa·s), the diameter of produced droplets decreases by a factor of up to 2 (Fig. 6b). The decrease in the droplet diameter with increasing viscosity is due to the fact that the viscous friction forces begin to compensate partly for the surface tension forces and, consequently, shorten the length of the capillary wave. The presence of a limiting viscosity above which atomization ceases is due to the complete compensation for the surface tension forces by the viscous friction forces. The surface tension has thereby a much weaker influence on the diameter of produced droplets, causing it to change by no more than 30% as the surface tension is increased from 22 to 72 mJ/m^2 (Fig. 6c). These data can be used for choosing regimes of action when the type of atomized liquid or its physical properties are changed.

Since in practical realization of the process of US atomization of the liquid the required diameter of produced droplets is provided by choosing the US vibration frequency [10], we obtained the dependence of the diameter of produced liquid droplets on the US vibration frequency (Fig. 7). From this dependence it follows that a decrease in the size of produced droplets is observed in the entire range of the investigated frequencies due to the fact that the length of the formed capillary wave decreases, since the velocity of its propagation in the liquid remains unaltered. However, beginning with a frequency of about 100 kHz, the rate of decrease in the droplet diameter decreases somewhat with increasing frequency. The obtained dependence shows that the atomization of liquids in the range of high frequencies (higher than 100 kHz) has prospects and it is necessary to develop new designs of high-frequency US vibration systems for atomizing liquids, since it will permit producing aerosols with a mean diameter of 10 μm or less. In general, the obtained dependences (Figs. 6 and 7) can form the

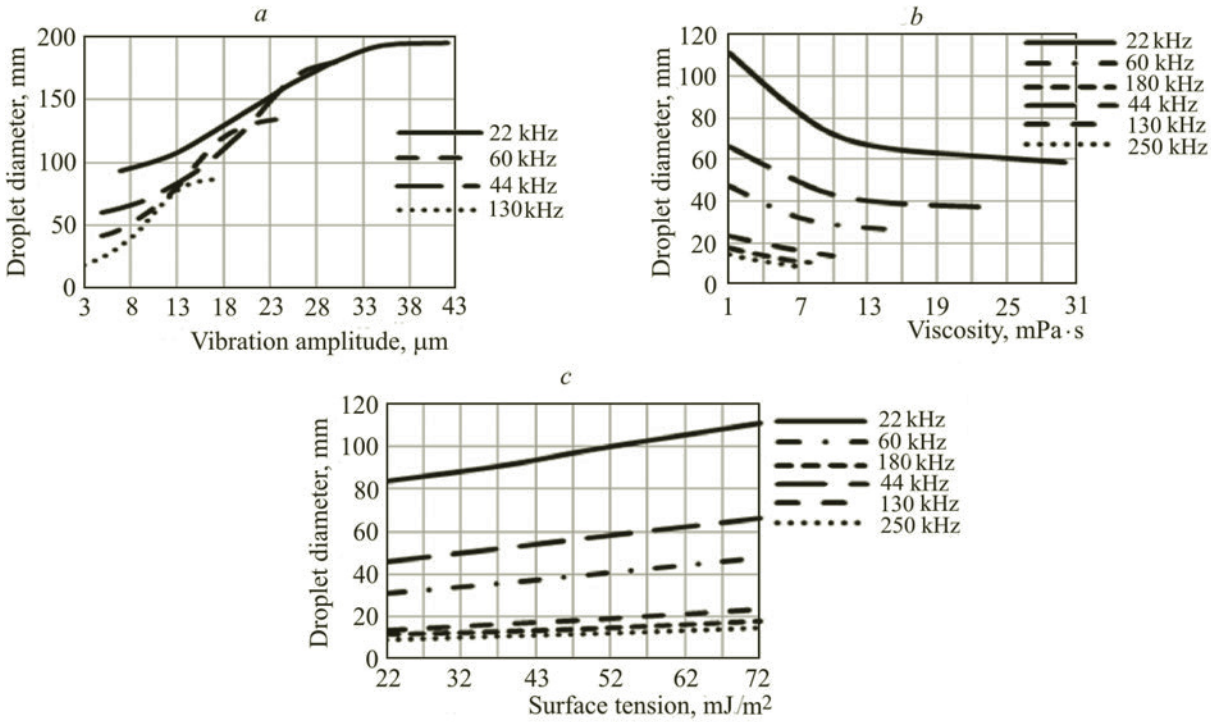

Fig. 6. Diameter of produced liquid droplets versus the vibration amplitude (a), the vibration amplitude (b), and the surface tension (c) at various frequencies.

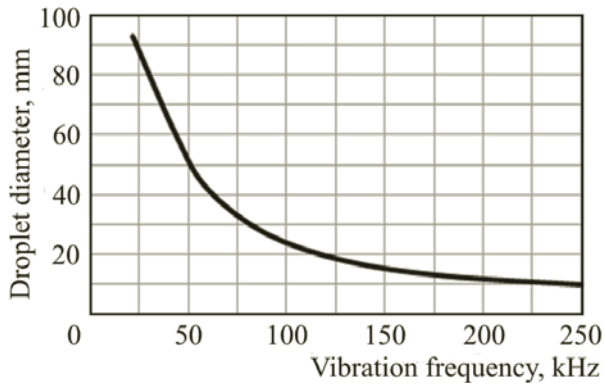

Fig. 7. Liquid droplet diameter versus the US frequency (for nonviscous liquids).

basis for determining the technical requirements (frequency and amplitude of the US action) for atomizers producing aerosols with a given dispersivity.

Determination of the atomization efficiency. The obtained dependences permit determining the most important parameter characterizing the efficiency of the atomization process, its specific efficiency (per unit area of the atomization surface), which we calculated by the formula:

$$\Pi = Vf N_s = a(\lambda^2 A/2\pi)(\pi^2/2 - 2) f N_s = a N_s \frac{P_{max}\theta}{2\pi\rho} \sqrt{\frac{\lambda c \theta(\pi^2 - 4)^2}{4\pi^2\left(\frac{\pi^2}{4} - \frac{1}{8}\right)}}, \quad (9)$$

where a is the correction factor taking into account the fraction of the volume of the capillary wave breaking down into droplets and assumed to be equal to 1 in theoretical calculations; N_s is the number of capillary waves per unit area of the

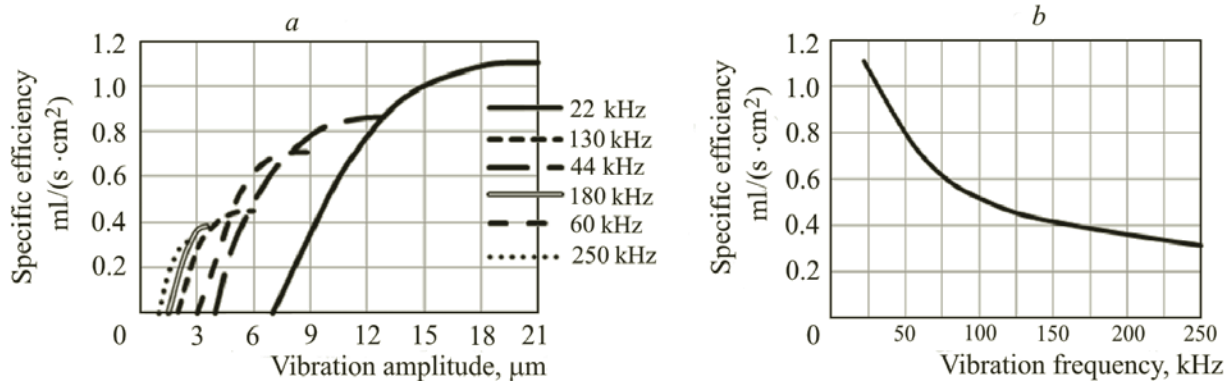

Fig. 8. Specific efficiency of atomization versus the US vibration amplitude (a) and frequency (b).

surface determined by the concentration of cavitation bubbles [2, 24]; V is the liquid volume separated from the capillary wave, m^3.

The obtained dependences of the specific efficiency of atomization on the regimes of US action are given in Fig. 8. From Fig. 8a it follows that there exists a limiting or optimal vibration amplitude, the exceeding of which terminates the increase in the efficiency. This is due to the limitedness of the shock pressure amplitude. Moreover, exceeding this amplitude degrades the dispersion characteristics of the aerosol (increasing the droplet diameters); therefore, for a frequency of 22 kHz the optimum amplitude is 17 μm, for 44 kHz it is 10 μm, for 60 kHz it is 7 μm, and for 130 kHz the optimum amplitude is 5 μm. The dependence presented in Fig. 8b also points to prospects of high-frequency US atomization of liquids (up to 250 kHz). It will make it possible to produce aerosols with an average diameter of 10 μm or less at an efficiency of more than 0.2 mL/s (from 1 cm^2 of the atomization surface). The obtained dependences form the basis for determining the technical requirements (frequency and amplitude of US action) for atomizers producing aerosols with given characteristics.

Experimental Verification of the Proposed Mathematical Model of Ultrasonic Atomization of the Liquid in the Layer. To verify the adequacy of the developed model, we made a number of ultrasonic atomizers operating in the revealed ranges of frequencies and amplitudes of ultrasonic vibrations. The design of each ultrasonic atomizer is based on the Langevin transducer [2, 16], whose vibrations are amplified by the concentrator and are then transferred to the atomization surface to make the liquid layer vibrate (Fig. 9). To perform experiments, we developed and used four ultrasonic atomizers having operating eigenfrequencies of 22, 40, 60, and 130 kHz.

To determine the reliability of the obtained theoretical results, we first compared the optimum thicknesses of the liquid layer found by calculations and obtained experimentally.

Experimental verification of the existence of an optimum thickness of the atomized liquid layer. The optimum thicknesses of the liquid layer at which the maximum energy is imparted to the free surface were determined in experiments indirectly by measuring the atomization efficiency related to the shock pressure near the "liquid–gas" interface by the proportional relation (6). During each measurement the layer thickness was fixed by regulating the flow rate of the liquid and controlling the resonance frequency of the ultrasonic vibration system in the precavitation regime linearly depending on the layer thickness [16].

The obtained experimental and theoretical dependences of the atomization efficiency on the layer thickness are given in Fig. 10. From Fig. 10 it is seen that the systematic error of the calculated optimum layer thickness at which the efficiency reaches its maximum is 0.22 mm. The presence of the systematic error is due to the assumption that the formation of capillary waves is most strongly influenced by cavitation bubbles in the immediate vicinity of the atomization surface. However, in practice it is necessary to take into account also the contribution of cavitation bubbles in the space between the surface of the working instrument and the free surface of the liquid.

Experimental determination of diameters of produced droplets in various regimes of ultrasonic atomization. To determine the droplet diameter, we used the optical method of low-angle scattering by particles of the aerosol cloud formed [23, 27]. Using the developed atomizers, we obtained the dependences of the mean diameter d_{10} of produced liquid droplets on the regimes of US action (vibration frequency and amplitude) and on the liquid properties most strongly influencing the atomization parameters: viscosity and surface tension (Figs. 11 and 12).

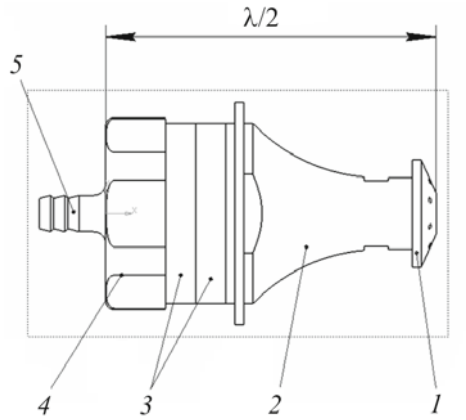

Fig. 9. Design of the ultrasonic vibration system for liquid atomization: 1) working instrument with atomization surface, 2) concentrator, 3) piezoelements (Langevin transducer), 5) pipe connection for supplying atomized liquid.

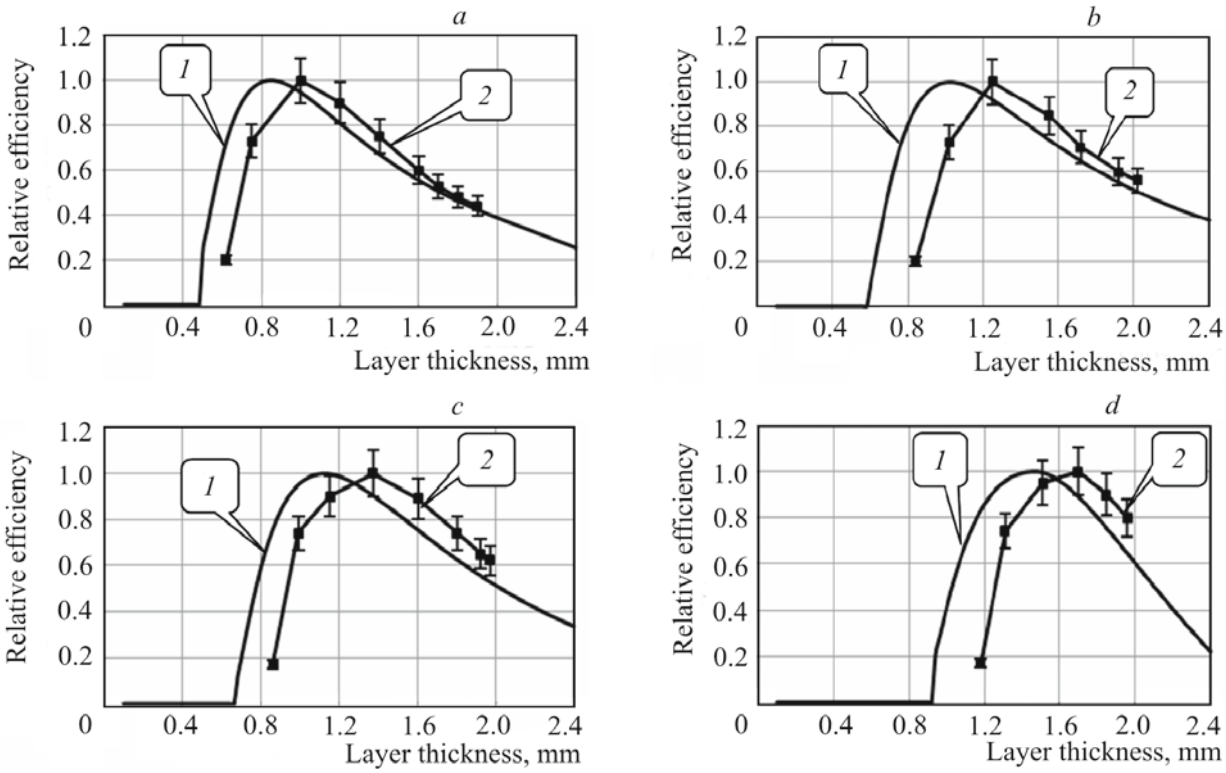

Fig. 10. Theoretical (1) and experimental (2) dependences of the relative atomization efficiency on the liquid layer thickness at various viscosities: a) 1 mPa·s, b) 10 mPa·s, c) 15 mPa·s, d) 30 mPa·s.

The relative discrepancy between the obtained experimental and theoretical data $\frac{|d_{ex} - d_{theor}|}{d_{ex}} \cdot 100\%$ does not exceed 20%. This confirms the adequacy of the model and the proposal made theoretically that it is expedient to increase the US atomization frequency to above 100 kHz and develop US vibration systems able to provide at the above frequencies ultrasonic action with amplitudes sufficient for atomizing liquids.

The further investigations were aimed at determining the efficiency dependence on the vibration amplitude of the atomization surface (Fig. 13). The obtained experimental data permit concluding that the efficiencies theoretically calculated

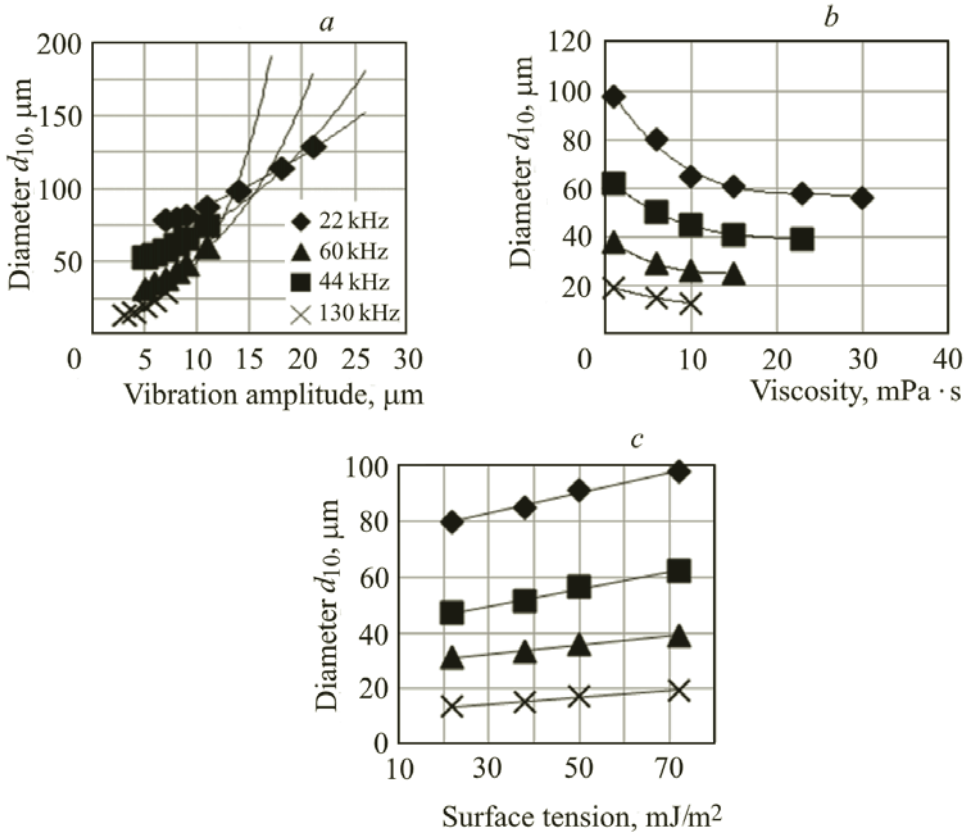

Fig. 11. Liquid droplet diameter versus the vibration amplitude (a), viscosity (b), and surface tension (c).

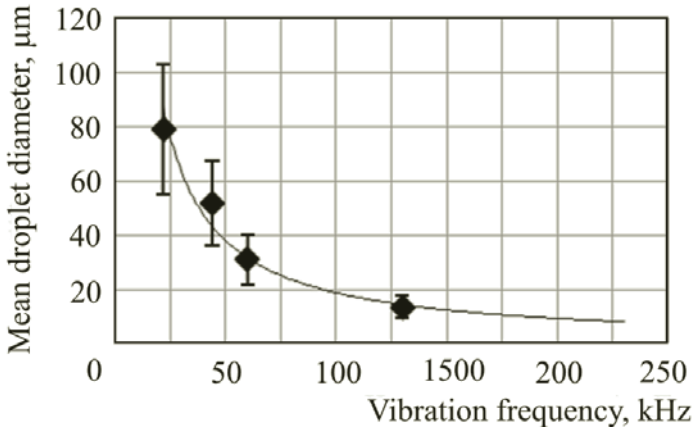

Fig. 12. Droplet diameter versus the vibration frequency of the atomization surface.

by expression (9) are easy to correct with the help of the correction factor *a* equal to 0.53 (9). Having analyzed the obtained dependences for various ultrasonic frequencies, we chose the value of the optimum amplitude of US vibrations at a level providing 0.8 of the difference between the maximum and the minimum atomization efficiencies. For instance, for the vibration frequency of the atomization surface of 22 kHz it will be 14 ± 3 μm; for 44 kHz, 8 ± 2 μm; for 60 kHz, 7 ± 1 μm; and for 130 kHz the optimum amplitude of US vibrations will be 5 ± 1 kHz. Figure 14 shows the dependence of the maximum specific efficiency of atomization on the US frequency obtained for the refined correction factor *a* (9). The given dependence can be used to determine the working frequency of atomization necessary for providing a given efficiency.

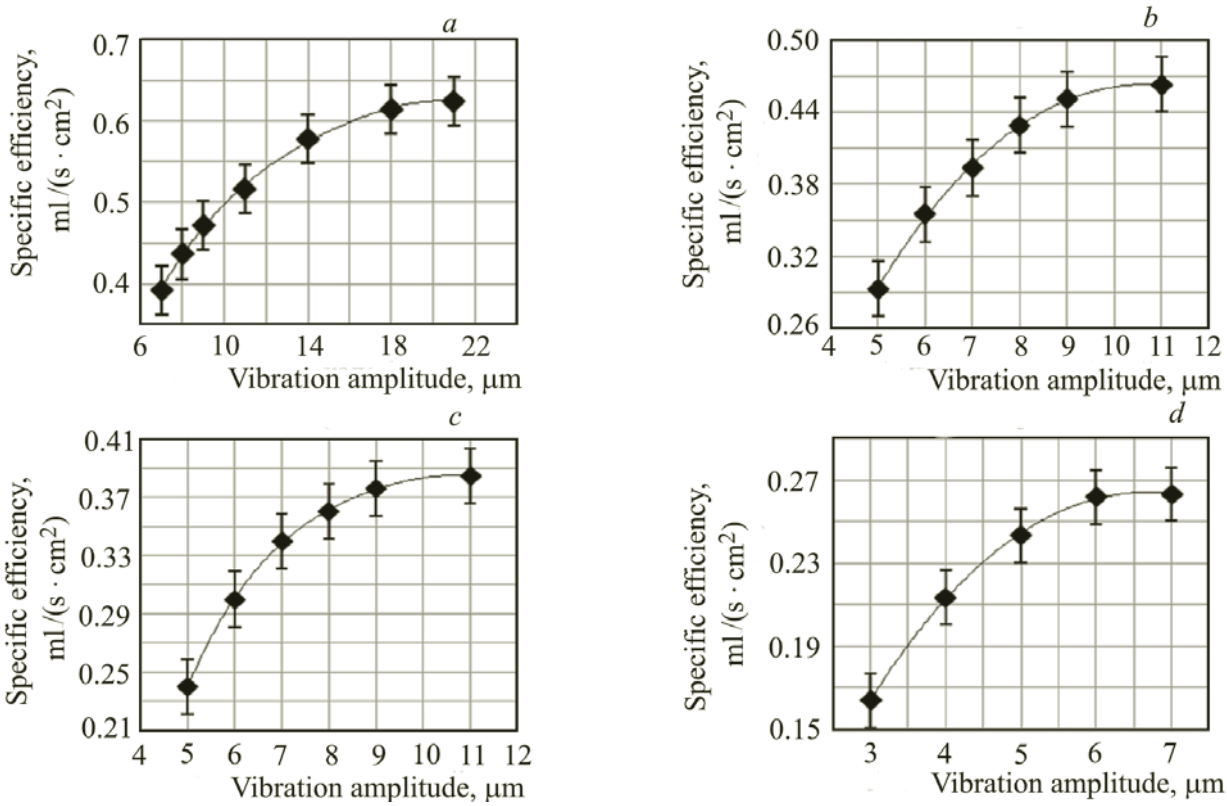

Fig. 13. Atomization efficiency versus the vibration amplitude of the atomization surface for various vibration frequencies: a) 22 kHz, 2) 44 kHz, c) 60 kHz, d) 130 kHz.

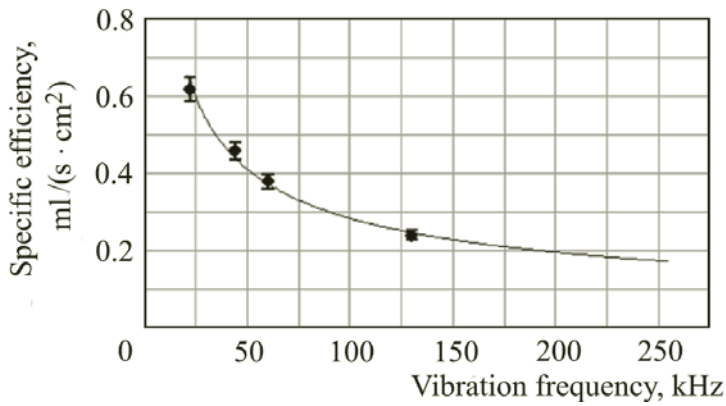

Fig. 14. Atomization efficiency versus the US frequency.

Thus, as a result of the investigations, we have fully determined the conditions and regimes of ultrasonic action for providing a spray cone with given efficiency and dispersivity characteristics for problems of applying coatings [4–6, 19] and realizing various chemical-technological processes in multiphase structures [7, 20, 23, 31].

CONCLUSIONS

As a result of the investigations made, the dependences have been determined of the efficiency of US atomization at various dispersion characteristics of produced aerosol with account for the physical properties of the liquid on the regimes of

ultrasonic action. The obtained dependences permit producing an aerosol with characteristics complying with the requirements of the process being realized due to the establishment of the necessary regimes of US action:

1. We have developed and propose an ultrasonic atomization model describing by steps the process of transformation of the energy of the initial ultrasonic action to the energy of increasing the free surface of the liquid (production of droplets), from the formation of cavitation bubbles to the detachment of droplets from the crests of capillary waves.
2. For the first time the dependences have been obtained for determining the atomization efficiency depending on the layer thickness at various properties of liquids. The regimes and conditions for providing the maximum atomization efficiency at a given dispersivity have been determined.
3. It has been shown that it is expedient to use the ultrasonic action at a frequency above 100 kHz in order to produce droplets of size 10 μm or less with an efficiency of no less than 0.2 mL/s.
4. It has been established that the optimum vibration amplitudes are 17 μm for a frequency of 22 kHz, 10 μm for 44 kHz, 7 μm for 60 kHz, and 5 μm for 130 kHz. It has been shown that if they are exceeded, then the efficiency ceases to increase and the dispersion characteristics of the spray degrade (the diameter of produced droplets increases).
5. The character and physical nature of the influence of liquid properties on the size of produced droplets have been established. It has been shown that as the viscosity is increased, the diameter of produced droplets is almost halved due to the fact that the forces of viscous stresses compensate for the surface tension forces. The surface tension has thereby a much weaker influence on the droplet diameter, causing its change by no more than 30% as the surface tension increases from 22 to 72 mJ/m^2.
6. The theoretically determined dependences have been verified by experiments with the use of the developed ultrasonic atomizers realizing the revealed vibration frequency and amplitude ranges.

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NOTATION

A, amplitude of the first-order wave component ($A = \max\limits_{t\in[0;2\pi];\,x\in[0;\lambda]} \xi^{(1)}(x, t)$), m; $A_{\max}$, maximum height of the crest of the capillary wave, m; a, correction factor taking into account the fraction of the volume of the capillary wave breaking down into droplets; B (Pa), n (dimensionless value), constants of the equation of fluid state $\dfrac{p + B}{\rho^n}$ = const; C, local velocity of sound in the liquid, m/s; c, velocity of sound in the liquid under normal conditions, m/s; D, mean diameter of droplets d_{10}; D_{avg}, average height thickness of the crest of the capillary wave, m; D_{ex}, experimental value of the mean diameter of droplets, m; D_{theor}, theoretical value of the mean diameter of droplets, m; f, US vibration frequency, Hz; h, liquid layer thickness, m; k, wave number of the capillary wave, m^{-1}; N_{s}, number of capillary waves per unit area of the liquid surface, m^{-2}; P_1, maximum pressure by collapse of the cavitation bubble, Pa; $P_{\max}$, pressure amplitude of the shock wave in the front near the free surface of the liquid layer, Pa; p, liquid pressure, Pa; $R_{\min}$, minimum radius of the cavitation bubble by collapse, m; u, velocity component of the liquid on the x axis, m/s; $u^{(n)}$, component of nth order of smallness of the velocity component of the liquid on the x axis equal to $U^{(n)}A_{\max}^n$, m/s; V, volume of the liquid separated from the capillary wave, m^3; v, velocity component of the liquid on the y axis, m/s; $v^{(n)}$, component of nth order of smallness of the velocity component of the liquid on the y axis equal to $V^{(n)}A_{\max}^n$, m/s; θ, collapse time of the cavitation bubble, s; λ, capillary wave length, m; ξ, capillary wave profile, m; $\xi^{(n)}$, component of nth order of smallness of the capillary wave profile equal to $E^{(n)}A_{\max}^n$, m; ρ, fluid density, kg/m^3; ω, angular frequency of US vibrations, s^{-1}. Subscripts: superscript (n), order of smallness of the term in expansion of liquid flow parameters near the free surface.

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