Journal of Applied Fluid Mechanics, Vol. 10, No. 5, pp. 1409-1419, 2017.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.18869/acadpub.jafm.73.242.26620

Determination of the Modes and the Conditions of Ultrasonic Spraying Providing Specified Productivity and Dispersed Characteristics of the Aerosol

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(Received June 2, 2016; accepted April 30, 2017)

ABSTRACT

For the spraying of liquids and the coating process at high-tech productions the method of ultrasonic spraying in a layer having a number of advantages such as low energy capacity, high productivity, fine-dispersity of obtained aerosol and the absence of spraying agent, is used. However the main problem of ultrasonic spraying application is the absence of the reliable dependences of spraying characteristics (drop diameter and spraying productivity) on the liquid properties (viscosity, surface tension), modes (frequency and vibration amplitude of spraying surface) and conditions (the thickness of liquid layer) of the ultrasonic action. In order to determine these dependences it is proposed the model based on cavitation and wave theory of the drop formation, which allows obtain for the first time theoretical ground of the existence of optimum thickness layer, at which free surface of liquid is acted upon by maximum energy providing drop detachment. The model analysis lets show advisability of the application of vibration frequency of more than 100 kHz for the drop generation with the size of 10 μm and less with the productivity of no less than 0.2 ml/s. Obtained results are proved by the experimental studies, which allow their use for the formulation of the technical requirements to the ultrasonic sprayers at the realization of different technological processes.

Keywords: Ultrasound; Spraying; Viscosity; Aerosol; Thickness of the layer; Capillary wave.

NOMENCLATURE

A	amplitude of component of the first order wave
$A_{\max}$	maximum height of the capillary wave crest
a	correction coefficient taking into account a portion of capillary wave volume fallen into drops
B, n	constant Tait equations of liquid state
c	sound speed in liquid
D	mean drop diameter d_{10}
D_{avg}	mean thickness of the capillary wave crest in height
d_{ex}	experimental value of the mean drop diameter
d_{theor}	theoretical value of the mean drop diameter
$E^{(n)}$	component of infinitesimal n- order of the capillary wave profile, equals to $E^{(n)}A_{\max}^{n}$
h	thickness of liquid layer
k	wave number of the capillary wave
N_S	number of the capillary waves per unit area of liquid surface
p	pressure in liquid
P_1	maximum pressure at the collapse of the cavitation bubble
P_m	amplitude of shock wave pressure in the front near the free surface of liquid layer
$P^{(n)}$	component of infinitesimal n- order of liquid pressure profile near free surface, equals to $P^{(n)}A_{\max}^{n}$
$R_{\min}$	minimum radius of the cavitation bubble at the collapse
u	component of liquid speed along the axis x
$U^{(n)}$	component of infinitesimal n- order of liquid x-velocity near free surface, equals to $U^{(n)}A_{\max}^{n}$
v	component of liquid speed along the axis y
V	volume liquid separated from the capillary wave
$V^{(n)}$	component of infinitesimal n- order of liquid y-velocity near free surface, equals to $V^{(n)}A_{\max}^{n}$
θ	collapse time of the cavitation bubble
ρ	liquid density
λ	capillary wave length
f	frequency of ultrasonic vibrations

ω	angular frequency of the ultrasonic vibrations
ξ	capillary wave profile
$^{(n)}$	infinitesimal order of the summand in the expansion of the parameters of liquid flow near the free surface

1. INTRODUCTION

The spraying of different liquids and coating process are the base for a large number of the technological processes at the productions dealing with the high-tech branches of the economy (Khmelev *et al.* 2011, 2012a, 2012c, 2014) (spraying of the substances for spectral analysis, photoresist spraying, coating of anticoagulating and inhibitory agents at the production of medical articles and implants, production of functional nanomaterials and many others).

Among other spraying methods (hydraulic, pneumatic, electrostatic and others) applied in practice (Donnelly 2005; Aliseda *et al.* 2008; Lugovskoy and Lyashok 2013; Balik 2014; Simon *et al.* 2015) the ultrasonic method (Donnelly 2005; Lugovskoy and Lyashok 2013; Simon *et al.* 2015) is the most widely used at high-tech branches of industry due to its high productivity and uniformity of obtained coatings, absence of the spraying agent, possibility of high-viscous liquid spraying.

At that in spite of long-term and successful application of the ultrasonic sprayers there are some unsolved problems, the main of which is the absence of reliable dependences of spraying features (drop diameter and spraying productivity) on liquid properties (viscosity, surface tension), modes (frequency and vibration amplitude of the spraying surface) and conditions (thickness of liquid layer) of the ultrasonic action. At that reason the parameters of the ultrasonic action providing the achievement of required features of spraying is set manually on the base of experience and visual observation of the process. Such setting does not allow provide optimum conditions of the spraying, that lead to worsening of dispersed characteristics of formed liquid drops and quality of coating.

That is why the task of formulation of single approach to the determination of conditions and modes of the ultrasonic action, which are necessary for providing spraying with specified characteristics of dispersity and productivity, is up-to-date and it requires analysis and studies of all processes occurring in a layer of sprayed liquid and leading to its spraying.

2. PHYSICAL MECHANISMS OF ULTRASONIC LIQUID SPRAYING IN A THIN LAYER

The mechanisms of local disturbances formation of liquid surface falling into drops at the ultrasonic action on a thin layer were considered by many Russian and foreign researchers (Donnelly 2005; Khmelev *et al.* 2011; Khmelev *et al.* 2012a, 2012c; Lugovskoy and Lyashok 2013; Ehrhorn and Semke 2014; Simon *et al.* 2015). At present there are 5 main mechanisms:

1) *formation of standing capillary waves due to border effect* appearing at the border of the flat area of the spraying surface covered with liquid layer and due to inertia of liquid to be sprayed;
2) *liquid displacement due to coherent jet* formed at the reflection of shock waves, which are generated at collapse of cavitation bubbles, from the spraying surface, in such case the profile of displacements is analogous to the profile of coherent jet velocity;
3) *liquid splashing above steam and gas bubbles* vibrating as a whole at its surface, in such case surface disturbances “liquid-gas” are caused by liquid splashing at the extension of cavitation bubbles.
4) *launching of standing capillary waves at the periodic action of the shock waves* to the border “liquid-gas” (cavitation and wave mechanism);
5) *damage of long-living steam and gas bubbles* pulsating near the liquid surface.

Depending on the mode cavitation development (Khmelev *et al.* 2015a, 2015b) in a layer of spraying liquid one or another mechanism prevails:

1. At *the mode of cavitation absence* it is evident, that mechanism 1 prevails. However in this case at high frequencies of ultrasonic action of more than 20 kHz the vibration amplitude of capillary waves does exceed vibration amplitude of the spraying surface (no more than 20 μm). The formation of drops does not occur. Even at low frequencies of action (no more than 300 Hz) according to the experimental studies (Ehrhorn and Semke 2014) the capillary waves generated due to the border effects are fallen into drops. The drop size at low-frequency action is more than 1 mm.

Thus, fine-dispersed spraying can be provided only at the generation of cavitation bubbles in a liquid layer.

2. At *the mode stable cavitation* Boguslavskyi and Eknadiosyants (Lugovskoy and Lyashok 2013) determined spraying mechanisms 2-4 based on the formation of shock waves at the collapse of cavitation bubbles. Nevertheless the results of the experimental studies (Khmelev *et al.* 2011, 2015a) allow define, that at stable cavitation mechanism 4 (cavitation and wave mechanism) prevails. It is caused by the fact, that at the realization of the mechanisms 2 and 3 the width of local liquid displacement at half-height can be compared with the thickness of layer (more than 0.5 mm) due to strong scattering of

coherent jet or spherically symmetrical liquid flow (at the extension of the cavitation bubble), as the bubble size is small in comparison with the layer size. This contradicts experimentally observed diameters of formed drops (no more than 120 μm) (Khmelev *et al.* 2011).

3. At *the mode of degenerating cavitation characterizing by the presence of long-living pulsating steam and gas bubbles* mechanism 5 prevails. However the drops formed at the mode of degenerating cavitation greatly vary in size (the difference is more than 100 μm), that is unacceptable for the number of the technological processes.

Thus ultrasonic fine-dispersed spraying should be performed at the mode of stable cavitation. Moreover cavitation and wave theory of liquid spraying is well-known and conventional at present.

Proposed model intended for determination of modes and conditions of ultrasonic action in order to provide spraying with specified characteristics, which is presented further, is based on this mechanism.

3. MODEL OF ULTRASONIC SPRAYING

In the frames of cavitation and wave theory the energy of ultrasonic vibrations of the spraying surface undergoes a number of changes:

1) US oscillations energy is transformed to cavitation bubbles appearance;

2) Cavitation bubbles energy is concentrated into shock wave energy with high amplitudes (up to 100 MPa);

3) Shock wave energy is transformed to capillary wave energy.

4) In finish, the capillary wave energy is transformed to spraying, i.e. the drops is formed from capillary waves crests.

The stages of energy transformation is presented in Fig. 1.

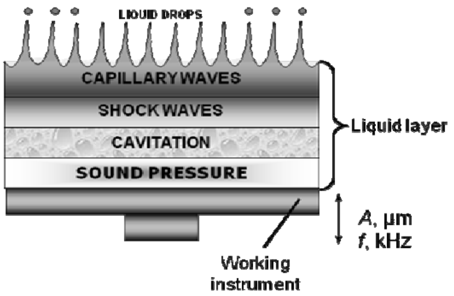


Fig. 1. Scheme of cavitation and wave mechanism of drop generation in the layer of spraying liquid.

That is why the model should consider all stages of energy transformation in the layer of spraying liquid, namely:

1) analysis of cavitation development in the layer of spraying liquid and generation of a shock wave appeared at cavitation bubble collapse and leading to capillary waves on free surface of liquid;

2) determination of capillary wave profile;

3) determination of the diameter of drops formed capillary wave crests and productivity of spraying depending on the wave profile.

These three stages of proposed model are described in details further.

3.1 Analysis of Cavitation Development in the Layer of Spraying Liquid

As sound pressure achieves maximum value at the vibrating surface (Khmelev *et al.* 2012c), the formation of cavitation bubbles in the layer bordering with the surface of the ultrasonic radiator is of practical interest.

At the collapse of the cavitation bubble near vibrating surface the shock wave propagating along the thickness of liquid layer is generated. When this shock wave achieves free surface, its pressure amplitude in the front according to Cole formula (Khmelev *et al.* 2012c; Lugovskoy and Lyashok 2013) is:

$$P_m = \frac{\rho c^2}{\sqrt{2}} \sqrt{\theta \frac{cP_1 R_{\min}}{B(n-1)}} \cdot \frac{1}{h \ln\left(h/R_{\min}\right)} \qquad (1)$$

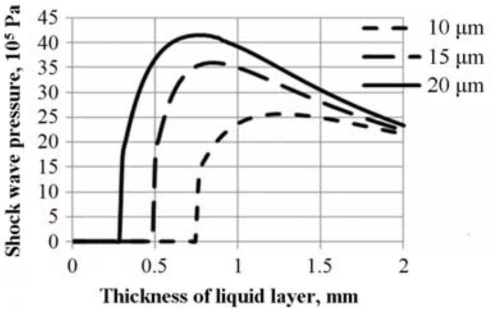
where θ is the time of cavitation bubble collapse, s; P_1 is the maximum pressure at the cavitation bubble collapse, Pa; $R_{\min}$ is the minimum radius of the cavitation bubble at the collapse, m defined at the base of Kirkwood-Bethe equation (Khmelev *et al.* 2012c; Khmelev *et al.* 2015b); h is the thickness of liquid layer, m; ρ is liquid density, kg/m^3.

On the base of the expression (1) we obtained the number of dependences of pressure amplitude of shock waves on the parameters of ultrasonic action, layer thickness and properties of spraying liquid (Fig. 2).

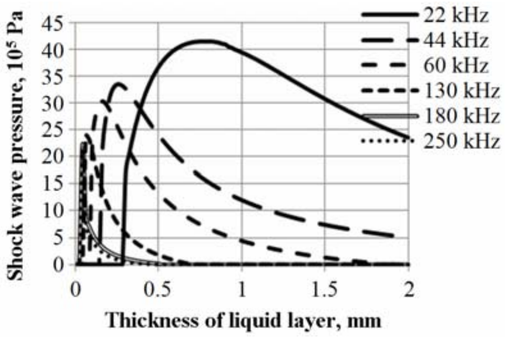
The dependences shown in Fig. 2 allow determine, that in a wide range of modes of ultrasonic action and physical properties of spraying liquid there is an optimum layer thickness, at which amplitude of shock wave pressure is maximum. The presence of optimum thickness is caused by the fact, that at smaller layer thicknesses shock wave pressure fall is due to decrease of amplitude of sound pressure in liquid (see expression (1)), and at high layer thickness shock wave pressure fall is caused by shock wave decay in the layer because of its scattering.

As the amplitude of shock wave pressure defines energy imparted to free surface and used further for drop formation, it can be considered, that at optimum thickness of layer maximum productivity of spraying can be achieved (Khmelev *et al.* 2012c).

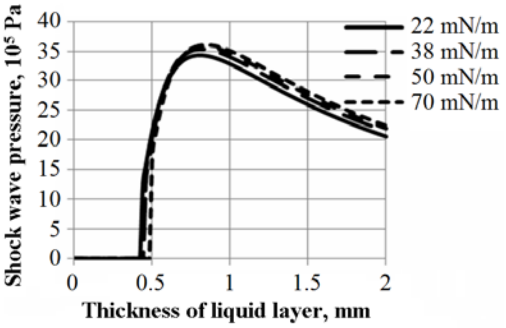
Obtained dependences of amplitude of shock wave pressure are the base for further definition of the profile of formed capillary waves.



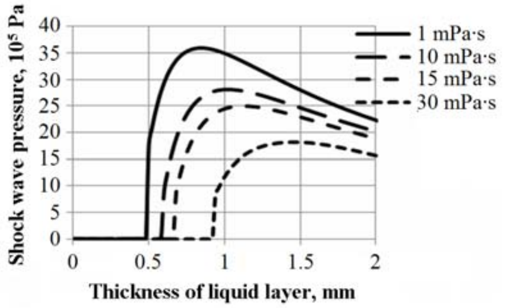
a) at different vibration amplitudes



b) at different frequencies of vibrations



c) at different surface tensions of liquid



d) at different viscosities of liquid

Fig. 2. Dependences of shock wave pressure (Pa) on the layer thickness of spraying liquid (mm).

3.2 Determination of Capillary Waves Profile

It is evident, that the capillary waves profile (Fig. 3) is determined by liquid flow near the border "liquid-gas", from which the drop detachment occurs.

This flow is described by Navier-Stokes equation with the boundary conditions of capillary jump on the free surface (Khmelev *et al.* 2012c).

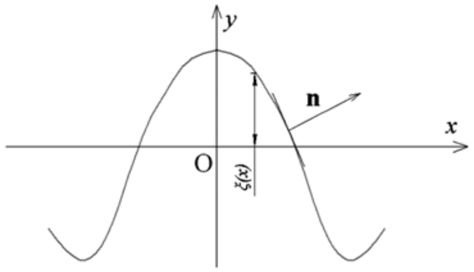


Fig. 3. Scheme of capillary wave near the free surface "liquid-gas" (ξ is the displacement of free surface, m; n is the normal vector to the free surface).

For the solution of non-linear Navier-Stokes equations we use the approach based on asymptotic expansion of vertical displacement ξ of the free surface, pressure p and component of medium velocity ($u=u_x$, $v=u_y$) in the form of infinite sums) (2):

$$\xi=\sum_{n=1}^{\infty}\xi^{(n)}=\sum_{n=1}^{\infty}E^{(n)}A_{\max}{}^{n}\;;$$

$$p=\sum_{n=1}^{\infty}p^{(n)}=\sum_{n=1}^{\infty}P^{(n)}A_{\max}{}^{n}\;;$$

$$u=\sum_{n=1}^{\infty}u^{(n)}=\sum_{n=1}^{\infty}U^{(n)}A_{\max}{}^{n}\;;$$

$$v=\sum_{n=1}^{\infty}v^{(n)}=\sum_{n=1}^{\infty}V^{(n)}A_{\max}{}^{n}\;, \qquad (2)$$

where superscript (n) means infinitesimal order of the summand (component) in the expansion of the value (Khmelev *et al.* 2012c); $A_{\max}$ is the maximum height of the capillary wave crest, m.

Specified asymptotic expansions allow obtain following expression for the capillary wave profile at the second approximation (3):

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

where $k=\dfrac{2\pi}{\lambda}$; λ is the length of capillary wave, m; A is the amplitude of the first order component wave ($A=\max\limits_{t\in[0;2\pi];\,x\in[0;\lambda]}\xi^{(1)}(x,t)$), m.

Value A (see expression (3)) depends on amplitude of shock wave pressure according to the following expression obtained on the base of the law of conservation of energy:

$$A=\frac{2P_m\theta}{\rho\omega\lambda}\sqrt{\frac{c\theta}{\lambda\left(\dfrac{\pi^2}{4}-\dfrac{1}{8}\right)}}\,. \qquad (4)$$

Fig. 4 shows the profiles of the capillary wave at its different amplitudes *A* (in relative units).

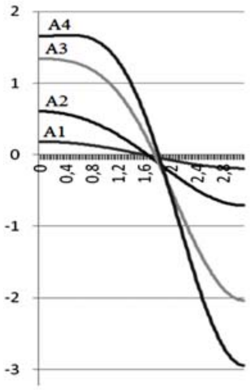


Fig. 4. Profile of the capillary wave at the different amplitudes (A4>A3>A2>A1) in relative units.

As it follows from Fig. 4, at ultrasonic spraying in the mode of stable cavitation the amplitude of capillary wave becomes comparable with its length (exceeds stability limit of the capillary wave – the amplitude exceeds 0.73 of its length (Eggers 1997). It explains the formation of the drops. At that mean thickness of local displacement of liquid mass is increased with the rise of the amplitude, that allows explain experimentally observed dependence of the drop diameter on the vibration amplitude of spraying surface (Khmelev *et al*. 2012a).

Found profile of the capillary wave is the base for determination of the diameter of formed aerosol drops. Obtained ratio and dependences of spraying characteristics (drop diameter and spraying productivity) on the modes of action and liquid properties are presented further.

3.3 Determination of Spraying Characteristics

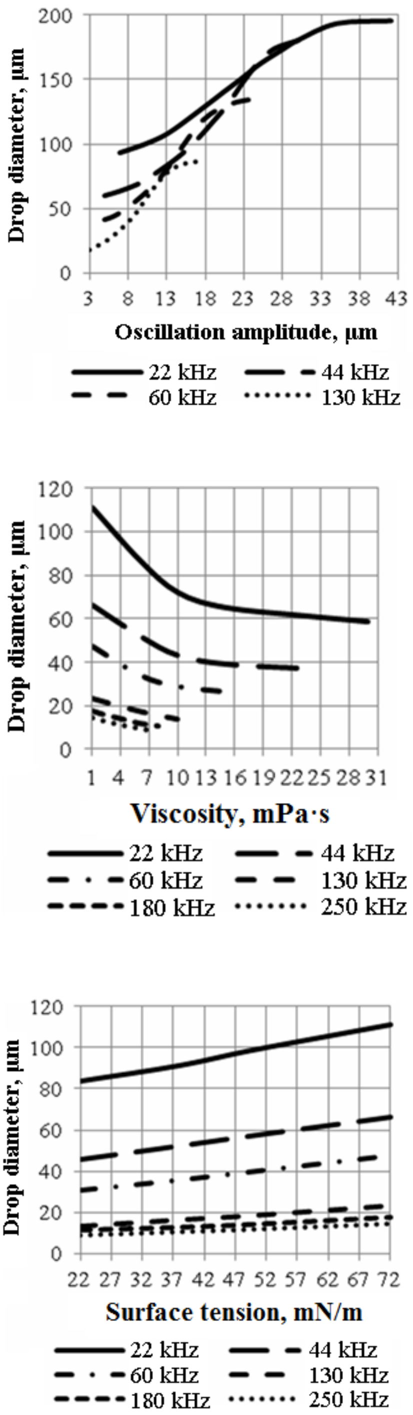
3.3.1 Determination of Spraying Drop Diameter

The diameter of the drops is defined on the base of obtained capillary wave profile with the use of breakup theory of Rayleigh jets (Khmelev *et al.* 2012c):

$$D = 1{,}89 D_{avg} = 3{,}68 \frac{\int_0^{\frac{\lambda}{2}} \left(\xi(x) - \xi\left(\frac{\lambda}{2}\right) \right) \partial x}{\xi(0) - \xi\left(\frac{\lambda}{2}\right)} . \qquad (5)$$

where D_{avg} is the mean thickness of capillary wave crest on height, m.

Obtained dependences of the diameters of formed drops on the physical liquid properties and amplitude of ultrasonic action are shown in Fig. 5. For each set of values of action modes and properties of sprayed liquid here and further the thickness of the layer is chosen optimum, at which amplitude of shock wave pressure is maximum (see Fig. 2).



a)

b)

c)

Fig. 5. Dependences of the diameter of formed liquid drops (micron) on the vibration amplitude (micron) (a), surface tension (mN/m) (b) and vibration amplitude (μm) (c) at different frequencies (kHz).

Presented dependences allow determine, that the dependence of formed drop diameter on vibration amplitude of spraying surface has non-linear character (Fig. 5a). For each of studied dependences there is specified amplitude of ultrasonic vibrations, at which excess further increase of the diameter of formed drops does not occur due to the limitation of the mean thickness of the capillary waves D_{avg} by the wave length λ (4, 5).

From the dependences shown in Fig. 5b it follows, that the increase of viscosity from 1 mPa·s (the viscosity of water) up to maximum value, above which the spraying stops (30 mPa·s – at the frequency of 22 kHz; 23 mPa·s – at the frequency of 44 kHz; 15 mPa·s – at the frequency of 60 kHz; 10 mPa·s – at the frequency of 130 kHz; 7 mPa·s – at the frequency of 180 kHz; 6 mPa·s – at the frequency of 250 kHz), leads to the decrease of the diameter of formed drops in up to 2 times (Fig. 5b). At that surface tension weakly influences on the diameter of formed drops, which changes in no more than in 30% at the increase of surface tension from 22 to 72 mN/m (Fig. 5c). These data can be applied for the choice of action modes at the change of spraying liquid type or change of its physical properties.

As for the practical realization of ultrasonic spraying process necessary diameter of formed drops is provided by the choice of frequency of ultrasonic vibrations of the spraying surface (Khmelev *et al.* 2012c), on the base of presented data, the dependence of the formed liquid drops diameter on the frequency of ultrasonic vibrations (Fig. 6) was obtained.

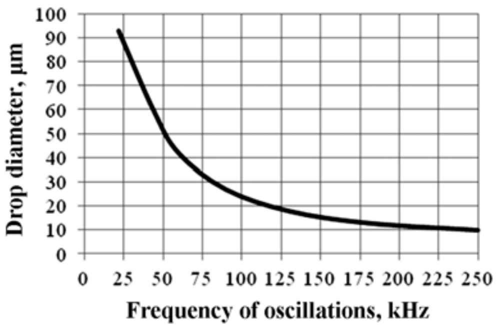


Fig. 6. Dependence of the diameter of formed liquid drops (micron) on the frequency of ultrasonic action (kHz) (for non-viscous liquid).

From presented dependences it follows, that decrease of formed drops size is observed in all range of studied frequencies. However starting from frequency of about 100 kHz the velocity of diameter drop decrease slightly falls with the growth of frequency.

Obtained dependence proves prospects of the application of ultrasonic liquid spraying in the range of high frequencies (more than 100 kHz) and necessity of development of new constructions of high-frequency ultrasonic vibrating systems for liquid spraying. It lets generate aerosols with the mean diameter of 10 µm and less.

The smaller diameter provides increased "liquid-gas" interface that increases of efficiency of many chemical engineering processes in heterogeneous systems. Furthermore, the smaller diameter of drops provides better uniformity of the applied coating.

In a whole given dependences (Fig. 5, 6) can be the base for the determination of the technical requirements (frequency and amplitude of ultrasonic action) to the sprayers providing formation of the aerosol with specified dispersity.

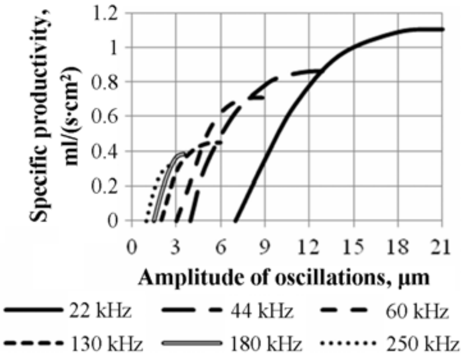
3.3.2 Determination of Spraying Productivity

The most important parameter characterizing efficiency of spraying process is its specific productivity (per unit area of the spraying surface), which is calculated by the formula (6):

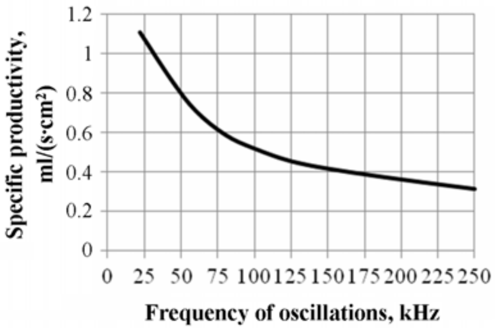
$$\Pi = VfN_S = a\left(\lambda^2 A/2\pi\right)\cdot\left(\pi^2/2-2\right)fN_S =$$
$$= aN_S\frac{P_m\theta}{2\pi\rho}\sqrt{\frac{\lambda c\theta\left(\pi^2-4\right)^2}{4\pi^2\left(\frac{\pi^2}{4}-\frac{1}{8}\right)}}\quad; \qquad (6)$$

where *a* is the adjustment coefficient taking into account portion of capillary wave volume fallen into drops, which is equal to 1 at the theoretical calculations; N_S is the number of capillary waves per unit area of the surface defined by the concentration of the cavitation bubbles (Khmelev *et al.* 2012c; Khmelev *et al.* 2015b); *V* is the liquid volume separated from the capillary wave.

Obtained dependences of specific productivity of the spraying on the modes of ultrasonic action are shown in Fig. 7.



a)



b)

Fig. 7. Dependences of specific productivity of spraying (ml/ (s·cm²)) on the amplitude (micron) (a) and frequency (kHz) (b) of ultrasonic vibrations.

According to obtained dependences (Fig. 7a) it is stated, that there is limit or optimum vibration amplitude, at which exceed productivity growth stops. It is caused by the limitation of amplitude of shock wave pressure. Further growth of amplitude leads to degeneration of cavitation bubbles into long-lived that corresponds breakages of graphs in Fig. 7a. Moreover exceed of specified amplitude worsens dispersed characteristics of the aerosol (the diameter of the drop increase – see Fig. 5a). That is why, for frequency of 22 kHz optimum amplitude, at which the productivity is achieved 95% from maximum (at graphs breakage), is 17 µm, for 44 kHz it is 10 µm, for 60 kHz it is 7 µm and for 130 kHz it is 5 µm.

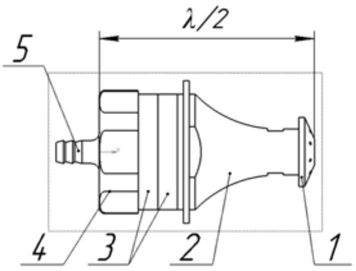
Presented in Fig. 7b dependence also proves the prospects of application of ultrasonic spraying method in the range of high frequencies (up to 250 kHz) and necessity to develop new constructions of high-intensity ultrasonic vibrating systems for spraying. It allows form aerosols with the mean diameter of 10 µm and less at the productivity of more than 0.2 ml/s (from 1 cm^2 of spraying surface), while the modern ultrasonic nebulizers working at frequency more than 0.5 MHz provide productivity of small diameter (less than 10 µm) aerosol spraying less than 0.04 ml/s.

Obtained dependences are the base for the formulation of technical requirements (frequency and amplitude of ultrasonic action) to the sprayers providing formation of the aerosol with specified characteristics.

Further the check of trueness of obtained results was performed by experiments.

4. EXPERIMENTAL STUDIES OF ULTRASONIC SPRAYING

For carrying out of experimental studies directed to prove adequacy of developed model we design several ultrasonic sprayers, which realize specified ranges of frequencies and amplitudes of ultrasonic vibrations. Langevin transducer is the base of the construction of each ultrasonic sprayer (Khmelev *et al.* 2012a, 2012c, 2015a), its vibrations are amplified by the concentrator and then they are transmitted to the spraying surface forcing vibrations of liquid layer (Fig. 8).

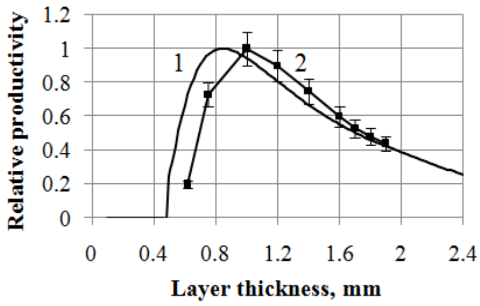


1–working tool with the spraying surface;
2–concentrator; 3–piezoelectric elements (Langevin transducer); 4–reflecting cover-plate;
5–connection for supply of spraying liquid

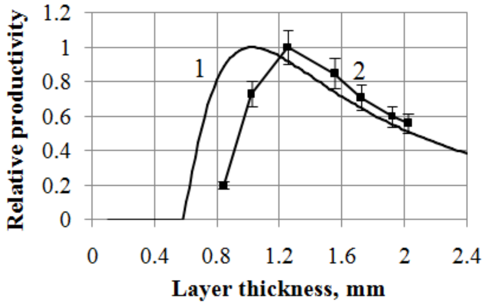
Fig. 8. Construction of the ultrasonic vibrating system for liquid spraying.

For the experiments we construct and use 4 ultrasonic sprayers having their own operating frequencies of 22, 44, 60 and 130 kHz.

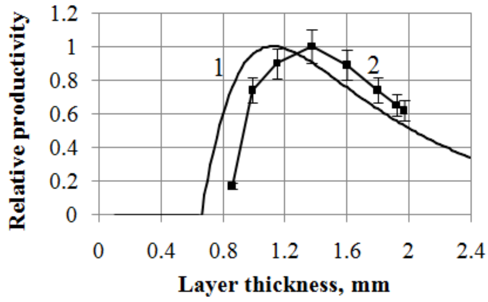
Initially for definition of validity of obtained theoretical results the optimum thicknesses of liquid layer found by the calculations and obtained experimentally were compared.



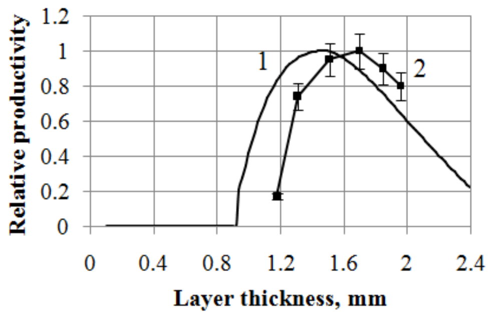
a) viscosity of 1 mPa·s



b) 10 mPa·s

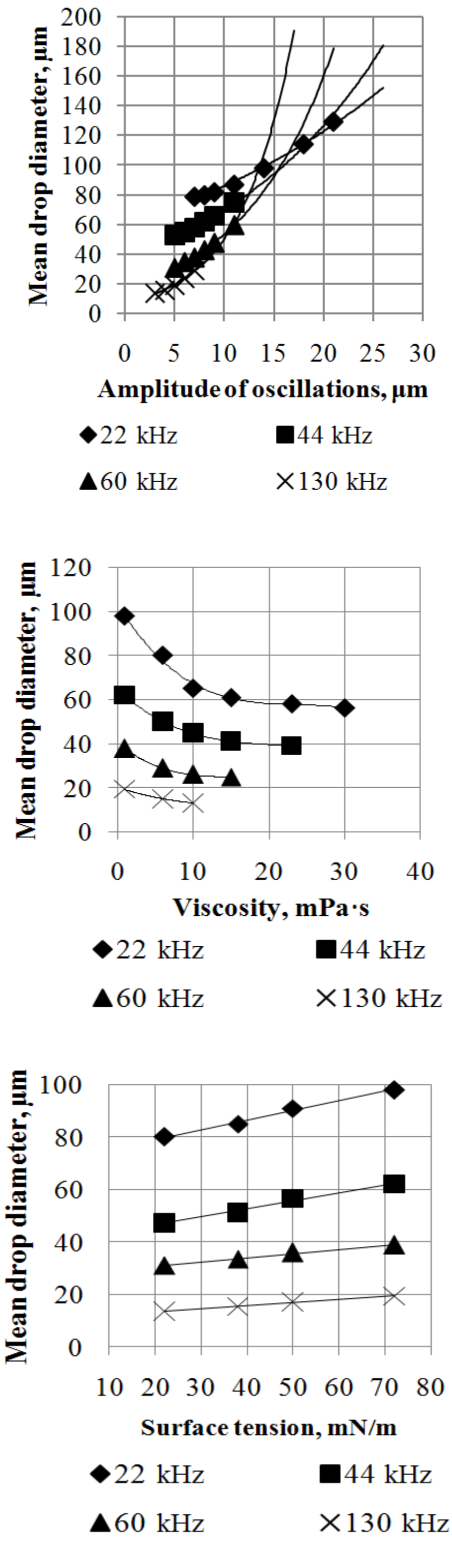


c) 15 mPa·s



d) 30 mPa·s

Fig. 9. Theoretical (1) and experimental (2) dependences of relative spraying productivity on the liquid layer thickness (mm) at different viscosities.



a)

b)

c)

Fig. 10. Dependences of the diameter of formed liquid drops (micron) on vibration amplitude (micron) (a), viscosity (mPa·s) (b) and surface tension (mN/m) (c).

4.1 Experimental Determination of the Optimum thicknesses of Liquid Layer

Experimental determination of the optimum thicknesses of liquid layer, at which free surface gets maximum energy, is carried out indirectly by the measurement of spraying productivity connected with pressure of the shock wave near the interface "liquid-gas" by the proportional dependence (see expression (6)).

During each measurement the layer thickness was registered by the adjustment of liquid output and control of resonance frequency of the ultrasonic vibrating system at the pre-cavitation mode depending on the layer thickness by the linear law (Khmelev *et al.* 2015a).

Obtained experimental and theoretical dependences of the spraying productivity on the layer thickness are shown in Fig. 9.

From obtained results it follows, that systematic inaccuracy of calculated optimum layer thickness, at which productivity achieves maximum, is 0.22 mm.

The presence of systematic inaccuracy is caused by the assumption, that cavitation bubbles located near the spraying surface greatly influence on the formation of capillary waves. However in practice there can be cavitation bubbles located between the surface of the working tool and the free liquid surface, which emit additional energy to the free surface.

Further we determine experimentally the characteristics of formed sprayer – drop diameter and spraying productivity – on the action modes (frequency and vibration amplitude) of the spraying surface.

4.2 Experimental Determination of the Diameters of Formed Drops at Different Modes of Ultrasonic Spraying

With the help of the sprayer data we obtain dependences of the mean diameter d_{10} of formed liquid drops on the modes of ultrasonic action (frequency and vibration amplitude) and properties of liquid influencing on the spraying parameters: viscosity and surface tension (Fig. 10, 11).

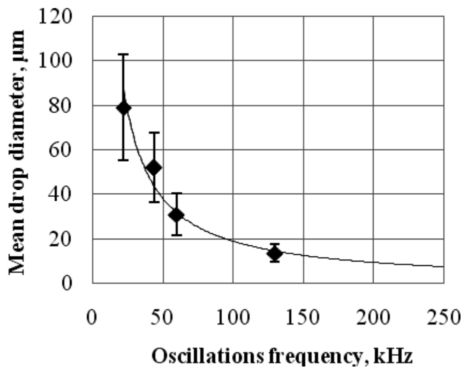
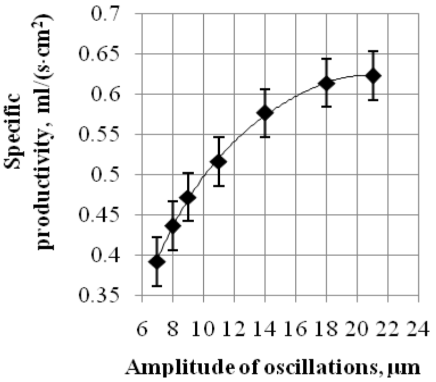
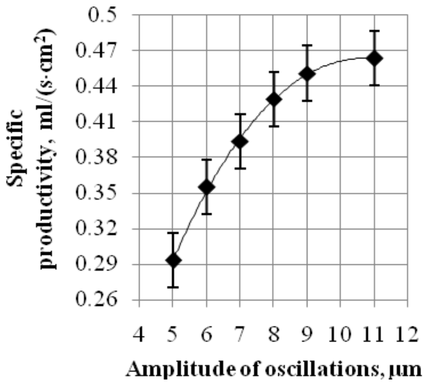


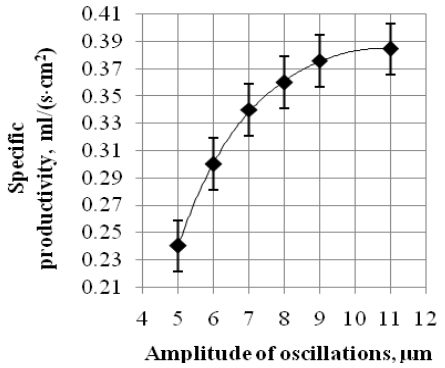
Fig. 11. Dependence of the drop diameter (micron) on frequency of vibrations (kHz) of the spraying surface.



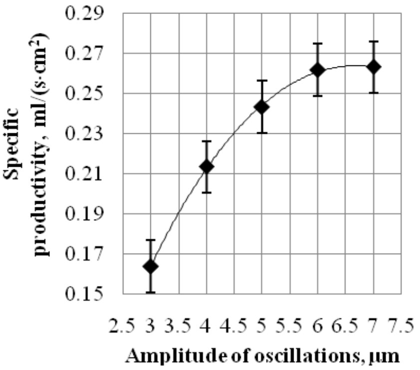
a) frequency of vibrations of 22 kHz



b) frequency of vibrations of 44 kHz



c) frequency of vibrations of 60 kHz



d) frequency of vibrations of 130 kHz

Fig. 12. Dependence of spraying productivity (ml/(s·cm²)) on vibration amplitude (micron) of the spraying surface for different frequencies.

Relative deviation of obtained experimental data with theoretical ones $\frac{|d_{ex}-d_{theor}|}{d_{ex}}\cdot 100\%$ does not exceed 20%. It proves adequacy of the model and theoretically stated assumption on appropriateness of frequency increase of ultrasonic spraying more than 100 kHz and design of the ultrasonic vibrating systems, which are able to provide action at specified frequencies with the amplitudes enough for liquid spraying.

Besides the mean diameter of aerosol drops the important characteristic of spraying process is its productivity, which increases with the growth vibration amplitude of the spraying surface (Fig. 12).

Obtained experimental data allow conclude, that the difference between theoretically calculated with the use of expression (6) values and measured values of specific productivity does not depend on the area of spraying surface determined by frequency of vibrations. Within this framework the adjustment coefficient *a,* equals to 0.53 (see expression (6)) was determined.

By the analysis of presented dependences for different frequencies of ultrasonic action the value of optimum amplitude of ultrasonic vibrations was chosen at the level providing 0.8 from the difference between maximum and minimum spraying productivity. For frequency of vibrations of the spraying surface of 22 kHz the amplitude is 14±3 μm, for 44 kHz – 8±2 μm, for 60 kHz – 7±1 μm and for 130 kHz – 5±1 μm.

Fig. 13 shows the dependence of maximum specific spraying productivity on frequency of ultrasonic action obtained for corrected adjustment coefficient *a* (see expression (6)).

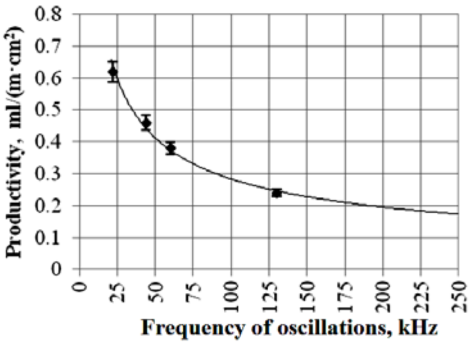


Fig. 13. Dependence of spraying productivity (ml/(s·cm²)) on frequency of ultrasonic action (kHz).

Obtained dependence can be used for determination of the operating spraying frequency, which is necessary for providing specified productivity.

Thus as a result of carried out studies we determined conditions and modes of ultrasonic action required for providing the sprayer with specified characteristics of dispersity and productivity.

5. CONCLUSION

As a result of carried out studies we proposed and developed the model of ultrasonic spraying, which step by step described the process of energy transformation of initial ultrasonic action into the energy of increase of free liquid surface (drop formation) beginning with the formation of cavitation bubbles and finishing drop detachment from capillary wave crests.

On the base of the analysis of developed model we determined interactions between the diameter of formed drops, spraying productivity, properties of liquid, modes (frequency and vibration amplitude of spraying surface) and conditions of action (layer thickness), namely:

1. For the first time it was obtained theoretical ground of the existence of optimum layer thickness and the dependences of amplitude of shock wave pressure defining energy to the free surface and spraying productivity on the thickness at different properties of liquid were found.

2. It was shown appropriateness of use of the ultrasonic action at the frequencies of more than 100 kHz for the formation of drops with the size of 10 μm and less with the productivity of less than 0.2 ml/s.

3. It was stated optimum amplitudes of vibrations, which is 17 micron for the frequency of 22 kHz, 10 micron for the frequency of 44 kHz, 7 μm for the frequency of 60 kHz and 5 μm for the frequency of 130 kHz and it was shown, that at their exceed the growth of productivity stopped, and dispersed characteristics of spraying became worse (the diameter of formed drops increased).

4. It was determined influence of properties of liquid on the size of formed drops. It was shown, that increase of viscosity led to decrease of the diameter of formed drops in 2 times. At that the surface tension slightly influenced on the diameter of formed drops causing its changes in no more than 30% at the growth of the surface tension from 22 to 72 mN/m.

Theoretically determined dependences were proved by the experimental studies with the application of designed ultrasonic sprayers realizing specified ranges of frequencies and vibration amplitudes.

Obtained results are the base for the formulation of technical requirements to the ultrasonic sprayers of liquids depending on the properties of liquid and necessary parameters of the sprayer for specified technological process.

ACKNOWLEDGEMENTS

The reported study was financially supported by RFBR. Project No. 16-38-60082 mol_a_dk.

The reported study was supported by Grant of President of Russian Federation No. MD-4753.2016.8.

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