High-frequency Vibration System for Liquid Atomization

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Abstract: - The article is devoted to the solution of problem of providing of high-productive fine-dispersed ultrasonic atomization due to the development of the new construction of the piezoelectric vibrating system of the ultrasonic atomizer intended for the operation at the frequencies of 120…250 kHz. The result of the study is the development and practical realization of the ultrasonic vibrating system providing the generation of high-dispersed aerosols with the size of the drops of 10…17 µm at the atomization productivity of 54 ml/min for 120 kHz and 14 ml/min for 250 kHz at consumed power of no more than 10 W for 120 kHz and 3 W for 250 kHz. The essential improvement of the atomization parameters was achieved due to the increase of area of the atomizing surface (2 cm^2 for 120 kHz and 0.5 cm^2 for 250 kHz) and providing of the vibration amplitudes of up to 15 µm at the frequency of 120 kHz and 10 µm at 250 kHz.

Keywords: - Ultrasound, transducer, working tool, atomization, dispersion, vibrating system

1. INTRODUCTION

The ultrasonic liquid atomization due to the number of advantages (the possibility of necessary productivity and dispersion providing without atomizing agents at high degree of homogeneity) is widely used: aerosol inhalations, atomization of disinfectant compositions, obtaining of high-dispersed powders, acceleration of the chemical reactions between liquid and gas reagents, coating, microencapsulation, etc. At that, the formation of high-dispersed aerosols with the sizes of the drops of 10…20 µm is highly demanded at present [1-10].

It is known, that the diameter of formed drops is determined by the frequency of ultrasonic vibrations and it can be defined by the expression (1), obtained by R. J. Lang [11]:

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

where σ is the coefficient of the surface tension of liquid, n/m; ρ is the density of liquid, kg/m^3; f is the frequency of ultrasonic vibrations, Hz.

From the expression (1) it follows, that for the formation of aerosol with the mean diameter of drops of about 20 µm the frequency of ultrasonic vibrations should be more than 100 kHz, and for 10 µm and less the frequency of ultrasonic vibrations should be more than 250 kHz (all the calculations are given for water) [12].

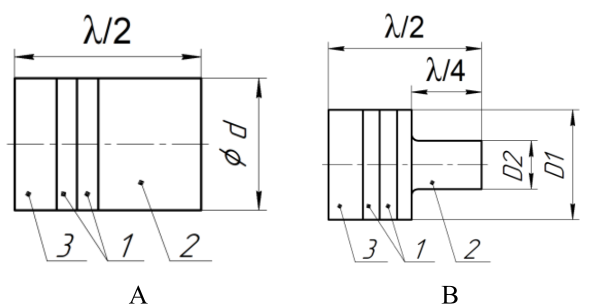
The development of the piezoelectric transducers for such frequencies presents no technical difficulties. However, for the atomization of liquids from the radiating surface of such transducers it is necessary to provide the amplitudes of vibrations of no less than 10 µm. To provide such amplitudes is possible only due to the application of the mechanical concentrators made in the form of metal rod of the variable diameter and, respectively, essential reduction of the radiating surface diameter of the ultrasonic atomizing device (up to 1…2 mm, i.e. the area is no more than 0.03 cm^2) [12-13].

Unfortunately, the productivity of the atomization from the unit of vibrating surface is inversely proportional to the frequency of ultrasonic vibrations, i.e. the increase of frequency up to 100…250 kHz leads to essential productivity decrease (less than 0.5…1 ml/min) in comparison with the atomization at the frequencies of 22….44 kHz (more than 60 ml/min) [12-13]. However, modern high-tech productions require high dispersion (the formation of the particles with the size of less than 20 µm) at increased in less than in 10 times atomization productivity [1-10, 14-16].

Well-known atomizing systems made by Sono-Tek, Sonics, Sonaer, Misonix are not able to provide above mentioned requirements to the dispersion and productivity of the aerosol formation that causes the necessity of the development of high-frequency ultrasonic vibration systems with increased atomization surface.

2. EXISTING CONSTRUCTIONS OF THE VIBRATION SYSTEMS OF THE ULTRASONIC LIQUID ATOMIZERS

The base of the most widely used constructions of the ultrasonic vibrating systems for the liquid atomization is Langevin piezoelectric transducer [17-18]. Such transducer is compact; it has high efficiency and provides the increase of vibration amplitude in up to 10 times at the application of concentrating working pad [19-20]. The sketch of Langevin piezoelectric transducer is shown in Figure 1A.



A – sketch of Langevin piezoelectric transducer;
B – piezoelectric transducer with the radiating pad in the form of stepwise concentrator; 1 – piezoelectric elements; 2 – radiating (atomizing) pad; 3 – reflecting pad;

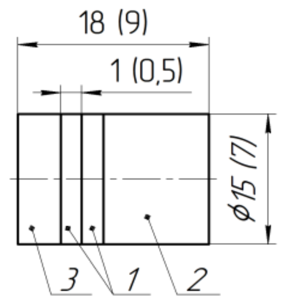
Figure 1. The sketch of Langevin piezoelectric transducer

The transducer consists of the piezoelectric elements (pos. 1), the radiating pad (pos. 2) and the reflecting pad (pos. 3). Total wave length (taking into account the differences of the propagation velocities of ultrasonic vibrations in the materials of the pads and the piezoelectric materials) of the radiating pad, two piezoelectric elements and the radiating pad corresponds to half wave length of generated vibrations. The attachment of additional pads to the piezoelectric elements (pos. 1) increases total length of the half-wave transducer and decreases its frequency. The radiating pad (pos. 2) in the transducer is made as a rule of titanium alloy (VT5), and the reflecting one (pos. 3) is made of steel (Steel 45). Such choice of the material provides efficiency increase of the transducer (rise of transformation ratio) regarding to the wave resistance of the radiating and reflecting pads [20, 21].

To increase vibration amplitude the radiating pad can be made in the form of stepwise concentrator (or with smooth transition) (Figure 1 B). Such half-wave design diagram allows combining quarter-wavelength piezoelectric transducer and concentrator of mechanical ultrasonic vibrations. The increase of the vibration amplitude up to necessary for the atomization leads to the reduction of the atomizing surface and the decrease of the atomization productivity [19].

The complexity of the development of classic Langevin transducer for the operating vibration frequency of more than 100 kHz is in its small longitudinal dimensions at the necessity of providing of the transducer diameter of less than half of the wavelength. If this condition fails, there are diametric and flexural modes decreasing operation efficiency of the piezoelectric transducer [17,20-23].

In practice it means, that the length of the transducer with the frequency of 120 kHz will be about 18 mm (for 250 kHz no more than 9 mm), at that its diameter should not exceed 15 mm (7 mm, respectively), and the piezoelectric elements will have dimensions of no more than 15x6x1(7x3x0.5). The sketch of Langevin piezoelectric transducer with the vibration frequency of 120 kHz with the dimensions is shown in Figure 2 (in brackets it is given the dimensions for the transducer with the frequency of 250 kHz).



1 – piezoelectric elements; 2 – radiating pad;
3 – reflecting pad

Figure 2. The sketch of Langevin piezoelectric transducer with the dimensions

The analysis of the construction of the piezoelectric transducer based on Langevin scheme allows revealing main disadvantages limiting its application in the ultrasonic vibrating systems with the frequencies of more than 100 kHz:

1. The use of cylinder Langevin transducers is limited due to low vibration amplitude of the butt-end of the radiating pad of the piezoelectric transducer, which is insufficient for liquid atomization.

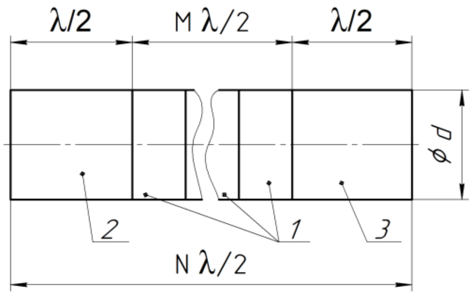
2. Mechanical destruction of the piezoelectric elements or decrease of operation efficiency of the piezoelectric transducer because of uneven pressing of the piezo ceramic elements between the radiating and reflecting pads due to small thickness of the pads.

3. Low atomization productivity caused by insufficient energy of vibrations generated on the atomizing surface because of small thickness of the piezoelectric elements [20, 21].

Thus, the production of such devices has some technical difficulties that cause the absence of high-frequency (100…250 kHz) radiators in the practice of ultrasonic atomization.

3. DEVELOPED CONSTRUCTION OF THE VIBRATING SYSTEM OF ULTRASONIC LIQUID ATOMIZERS

To eliminate disadvantages of classic Langevin transducer and to increase energy of high-frequency vibrations generated on the atomizing surface it was proposed the construction of ultrasonic piezoelectric transducer shown in Figure 3.

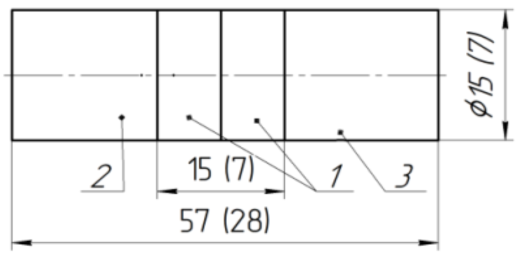


1 – piezoelectric elements;
2,3 – pressing half-wave pad

Figure 3. Construction of developed piezoelectric transducer

The transducer is made of even number (2*M) of the piezoelectric elements (pos. 1) (where M – 1, 2, 3…) and two pressing half-wave pads (pos. 2 and pos. 3). In developed construction of the piezoelectric transducer the thickness of each piezoelectric element (pos. 1) is chosen equal to a quarter wave-length of generated vibrations in piezoelectric material, i.e. total length of all piezoelectric elements (pos. 1) corresponds to M half wavelength. Thus, the piezoelectric elements represent independent ultrasonic electroacoustic transducer providing the generation of ultrasonic vibrations with necessary frequency. In order to ensure compression of the piezoelectric elements (made in the form of discs with a central opening) it is used metal stud tightening pressing half-wave pads, which frequency should also correspond to the frequency of the piezoelectric elements. So, for instance, to provide operation at the frequency of 120 kHz (if the velocity of propagation of ultrasonic vibrations in the piezoelectric material is 3600 m/s) the thickness of each two piezoelectric elements should equal to 15 mm (taking into account the thickness of copper contact electrodes it is necessary to have two piezoelectric elements with the thickness of 7 mm each). For the generation of ultrasonic vibrations with the frequency of 250 kHz the total thickness of two piezoelectric elements should be 7.2 mm (two piezoelectric elements with the thickness of 3.5 mm each). Thus, in developed transducer (which consists of 2 quarter-wave piezoelectric elements) the volume of the piezoelectric ceramics is in 7 times more than in classic construction of Langevin transducer and respectively energy of the vibrations generated by the transducer is significantly higher.

To study functional possibilities of proposed construction it was produced pilot samples of the piezoelectric transducers for the frequencies of 120 kHz and 250 kHz. Figure 4 shows the sketch and the photo of the transducers (in the brackets it is given dimensions for the transducer with the frequency of 250 kHz).



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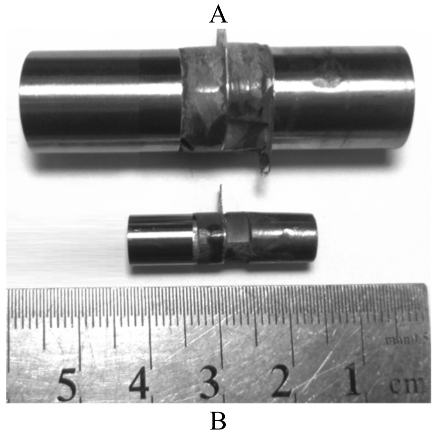


B

A – sketch of the piezoelectric transducer;
B – photo of the piezoelectric transducers;
1 – piezoelectric elements;
2, 3 – pressing half-wave pad

Figure 4. Developed piezoelectric transducers

For carrying out comparative experimental studies it was also designed piezoelectric transducers (120 and 250 kHz), in which it was installed the stepwise concentrator as a half-wave pad 3 with the transformation ratio equal 4. The calculation of the concentrators is carried out by engineering design procedures proposed in papers [21-23]. Figure 5 shows the sketch of the stepwise concentrator.

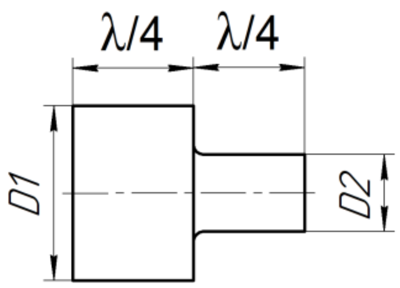
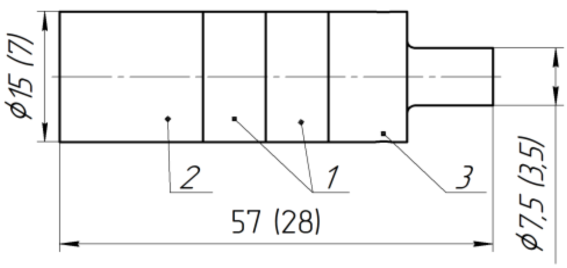


Figure 5. Sketch of the stepwise concentrator



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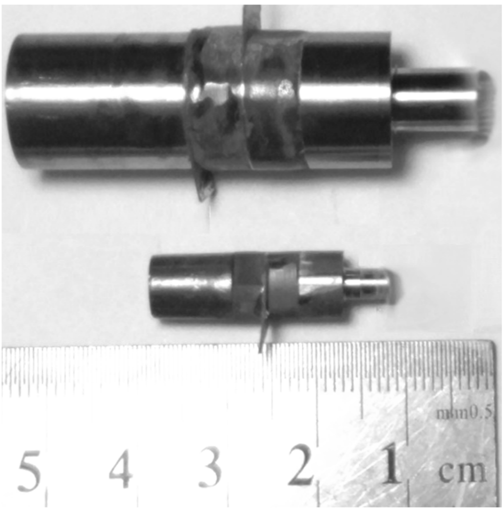


B

A – sketch of the piezoelectric transducers;
B – photo of the piezoelectric transducers;
1 – piezoelectric elements; 2 – pressing half-wave pad;
3 – pressing half-wave pad – the concentrator of mechanical vibrations;

Figure 6. Developed piezoelectric transducers

The ratio between input (D_1) and output (D_2) diameters is defined by the expression:

$$\sqrt{K} = \frac{D_1}{D_2} \tag{2}$$

where K is the transformation ratio of the concentrator; D_1 and D_2 are the input and output diameters of the concentrator, respectively, m.

The length of the half-wave concentrator is defined by the expression:

$$L = \frac{\lambda}{2} = \frac{c}{2f} \tag{3}$$

where c is the velocity of sound in the material of the concentrator, m/s; f is the natural frequency of vibrations, Hz; λ is the wave-length, m.

Figure 6 shows the sketch and the photo of developed transducers (in the brackets it is given dimensions for the transducer with the frequency of 250 kHz).

The measurements of the amplitude of mechanical vibrations of butt-end surface of the pressing half-wave pad (pos. 3) carried by stroboscopic method [24, 25], and also measurements of electric power consumed at that time are given in Table 1.

Table 1. Characteristics of developed piezoelectric transducers

Characteristic	Value	
Form of pressing half-wave pad 3	Cylinder/ Stepwise concentrator	Cylinder/ Stepwise concentrator
Natural frequency of vibrations, kHz	120	250
Amplitude of mechanical vibrations, μm	1 / 4	0.6 / 2.5
Consumed power, W	3	1.4

The analysis of obtained data proves operating capacity of proposed construction and possibility of essential increase of vibration amplitude (in about 4 times) due to the application of the stepwise concentrator. However, obtained vibration amplitude is insufficient for the realization of the atomization process at high frequencies.

4. DEVELOPMENT OF THE CONSTRUCTION OF MULTISTAGE CONCENTRATOR

To increase vibration amplitude up to the values, at which liquid atomization starts (about 7-10 μm at the frequency of 120 kHz and 5-7 μm at the frequency of 250 kHz [26-28]) it is proposed to use several series-connected concentrators [29]. At that total transformation ratio for the ultrasonic vibrating system is calculated by the expression (4):

$$K = \frac{A_{out}}{A_{in}}, \tag{4}$$

where A_{out} is the required vibration amplitude of atomizing surface of the concentrator, μm; A_{in} is the vibration amplitude of the butt-end surface of the piezoelectric transducer, μm.

Total transformation ratio of the concentrators applied in the ultrasonic vibrating systems is determined by the product of the transformation ratio of each concentrator:

$$K = K_1 \cdot K_2 .... K_N , \tag{5}$$

where $K_1 ... K_N$ is the transformation ratio of the concentrators, N is the number of the concentrators. At that to simplify the calculations the values of the transformation ratio $K_1 ... K_N$ can be equal, i.e.:

$$K_1 = K_2 = ... K_N \tag{6}$$

Taking into account the expression (6) and the substitution (4) into (5) it is obtained:

$$N \cdot K_N = \frac{A_{out}}{A_{in}} , \tag{7}$$

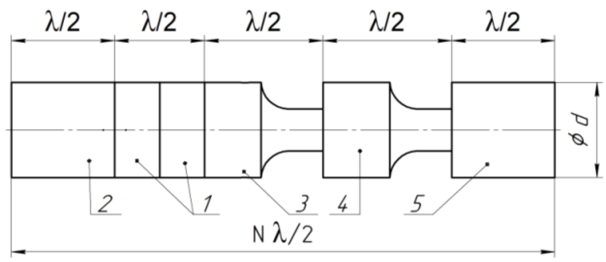
from which the number of the concentrators N will be:

$$N = \frac{A_{out}}{A_{in} \cdot K_N} \tag{8}$$

Thus, given expression (8) allows calculating the number of the concentrators and the transformation ratio of each from them, on condition that K_N is set within the range of 3 to 5. The realization of the concentrator with the transformation coefficient lower than specified range leads to irrational increase of the concentrator number and consequently the length of the atomizer construction. In turn, the rise of the transformation ratio of more than 5 causes mechanical stress in the zone of the step junction and in some cases to its mechanical failure. The geometric dimensions of each concentrator (see Figure 5) are defined by the expressions (2) and (3).

5. PRACTICAL CONSTRUCTIONS OF THE ULTRASONIC ATOMIZERS

On the base of proposed construction, it was developed ultrasonic vibrating systems for liquid atomization (Figure 7) containing two concentrators (pos. 3 and pos. 4) and the resonance atomizing unit (pos. 5). For both vibrating systems (120 kHz and 250 kHz) the total transformation ratio of the concentrators equals to 16 (the transformation ratio of each concentrator is 4).

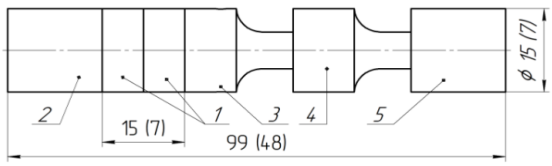


1 – piezoelectric elements; 2 – pressing half-wave pad; 3 – pressing half-wave pad – concentrator of mechanical vibrations; 4 – additional concentrator of mechanical vibrations; 5 – resonance atomizing unit

Figure 7. Sketch of developed ultrasonic vibrating systems

The distinctive feature of proposed constructive scheme is the application of the resonance atomizing unit (pos. 5). Owing to it the increase of the area of the atomizing surface without loss of vibration amplitude is achieved [29].

To study functional possibilities of developed atomizers it was produced pilot samples of the ultrasonic vibrating systems (with the frequencies of 120 kHz and 250 kHz). Figure 8 shows the sketch and the photo of developed ultrasonic vibrating systems for liquid atomization (in the brackets it is given dimensions for the transducer with the frequency of 250 kHz).



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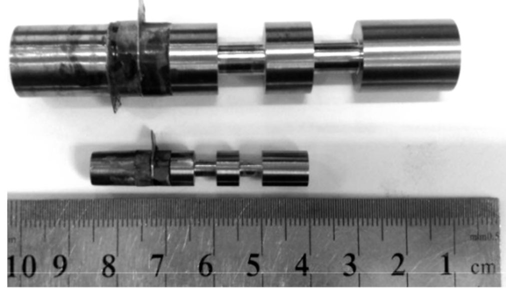

B

A – sketch of the piezoelectric transducers;
B – photo of the piezoelectric transducers;
1 – piezoelectric elements; 2 – pressing half-wave pad; 3 – pressing half-wave pad – concentrator of mechanical vibrations; 4 – additional concentrator of mechanical vibrations; 5 – resonance atomizing unit

Figure 8. Sketch and photo of developed ultrasonic vibrating systems

As the concentrators (pos. 3 and pos. 4) and the resonance atomizing unit (pos. 5) are made in one piece, the measurements of the natural vibration frequencies of the elements of the ultrasonic vibrating system are not possible. That is why; it was determined natural vibration frequency of all ultrasonic vibrating system. The amplitude of mechanical vibrations of the atomizing surface was measured by stroboscopic method [24-25].

It was carried out experimental studies, which allow determining maximum atomization productivity (for water) and the mean diameter of formed drops. The diameters of generated drops were measured by drop capture by the immersion medium [30]. Table 2 shows the results of the experimental studies.

Table 2. Technical characteristics of developed ultrasonic vibrating systems

Characteristic	Value	
Natural vibration frequency, kHz	120	250
Amplitude of mechanical vibrations, μm	15	10
Calculated total transformation ratio	16	16
Consumed power without load, W	3	1.4
Consumed power at maximum atomization productivity, W	10	3
Area of atomizing surface, cm^2	2	0.5
Productivity of water atomization, ml/min	54	14
Mean diameter of formed drops, μm	17	10

The analysis of obtained results of the measurements showed, that developed ultrasonic vibrating systems combine high power characteristics of the piezoelectric transducer (10 W for 120 kHz and 3 W for 250 kHz), high vibration amplitude (15 μm for 120 kHz and 10 μm for 250 kHz) provided due to the application of several concentrated units and large area of the atomizing surface (2 cm^2 for 120 kHz and 0.5 cm^2 for 250 kHz). Due to this fact it is provided the atomization productivity of 54 ml/min for 120 kHz ultrasonic vibrating system and 14 ml/min for 250 kHz ultrasonic vibrating system.

6. CONCLUSION

The problem of productivity increase of the ultrasonic atomization at the frequencies of higher than 100…250 kHz was solved due to the development of new type of the piezoelectric transducer and consistent installation of necessary number of the mechanical concentrators with the atomizing surface of required area. It became possible due to the application of new approach to the design of the piezoelectric vibrating systems of the ultrasonic liquid atomizers including the use of electroacoustic transducer of increased power, which made of even number of the piezoelectric elements and two pressing half-wave pads. At that the thickness of each piezoelectric element was chosen equal quarter wave-length of generated vibrations in the piezoelectric material, and the total length of all piezoelectric elements corresponds to even number of quarters wave-length.

To achieve vibration amplitude sufficient to liquid atomization the concentrating units – transformers of vibration velocity were installed in series. For the enlargement of the area of the atomizing surface without loss of the vibration amplitude the atomizing tool made in the form of cylinder resonance unit with the diameter of less than half of wavelength is applied.

To prove the efficiency of proposed approach it was developed, produced and studied ultrasonic vibrating systems providing the formation of high-dispersed aerosols with the mean diameter of drops of 10…17 μm at the atomization productivity of 54 ml/min for 120 kHz and 14 ml/min for 250 kHz, if consumed electric power is no more than 10 W for 120 kHz and 3 W for 250 kHz.

During the study it was determined, that essential improvement of the atomization parameters was achieved due to the increase of the area of the atomizing surface (2 cm^2 for 120 kHz and 0.5 cm^2 for 250 kHz) and providing of the vibration amplitude of up to 15 μm at the frequency of 120 kHz and 10 μm for 250 kHz.

ACKNOLEDGEMENTS

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