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A method of spraying based on hydrodynamic and ultrasonic influence on the sprayed liquid

Andrey V Shalunov, Viktor A Nesterov and Dmitriy V Genne

Biysk Technological Institute (branch) of the Altay State Technical University, Biysk, Russia

E-mail: nva@u-sonic.ru

Abstract. The article is devoted to the development of a sprayer based on the method of simultaneous hydrodynamic and ultrasonic influence on the flow of sprayed liquid. The proposed spraying method makes it possible to increase spraying productivity while reducing the size of aerosol droplets. By establishing optimal conditions, with a nozzle diameter of 0.7 mm, an ultrasonic tool diameter of 8 mm and an excess pressure of the sprayed liquid of 0.7 MPa, the atomizer provides a productivity of 9 ml/s and forms an aerosol with droplet sizes $D_{32} = 40$ μm. This is primarily due to the establishment of the optimal operating mode and conditions in the cavitation zone, which make it possible to ensure the highest quantitative concentration of cavitation bubbles.

1. Introduction

Spraying liquids and spraying various coatings is the basis of a significant number of technological processes in industries, primarily related to high-tech production sectors [1-3]. For the effective implementation of modern technologies, it is necessary to create aerosols with increased requirements for monodispersity, spray density and the size of the formed droplets. In this case, one of the main tasks is the creation of high-performance, highly dispersed spraying systems.

Hydraulic, pneumatic and electrostatic methods are the most common types of sprayers and spraying methods. They do not allow the creation of highly dispersed aerosols with the required particle sizes and required productivity. As a rule, high-performance spray systems form an aerosol with large droplet sizes, while highly dispersed spray systems have low productivity [4-5].

The problem can be solved by combining hydrodynamic and ultrasonic effects on the jet of sprayed liquid.

2. Description of the sprayer design

The authors proposed a sprayer based on hydrodynamic and ultrasonic effects (Figure 1).

The sprayer, based on hydrodynamic and ultrasonic action, contains an ultrasonic oscillatory system consisting of a piezoelectric transducer (#1) and a working tool (#5).

A technological volume is installed on top of the working tool (#6). The sprayed liquid (#9) is supplied to the technological volume (#6) through the fitting (#8).

The generated aerosol flows through the hole in the nozzle (#7), while the hole is located opposite the end oscillating surface of the working tool (#5). The jet is made replaceable, which ensures quick replacement of one jet with another jet.

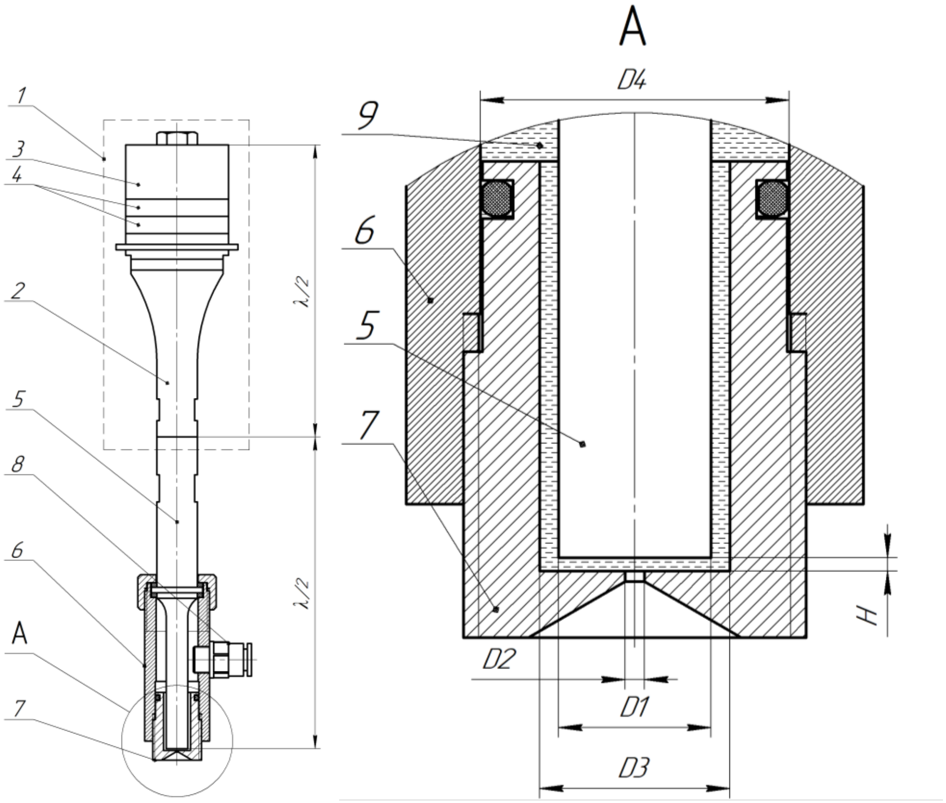


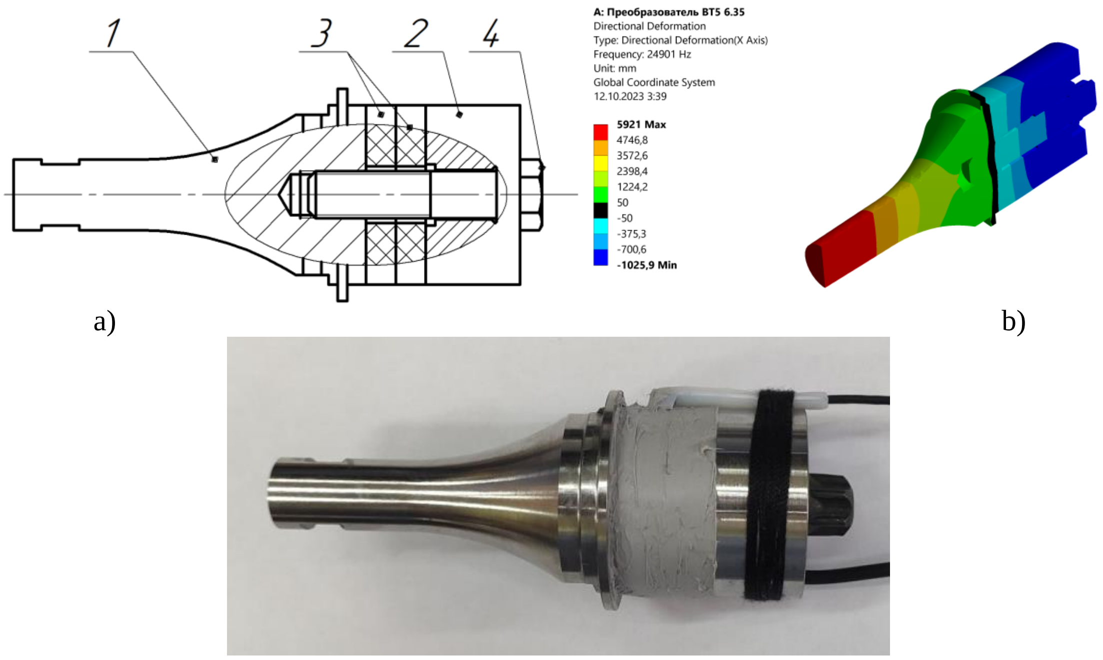
Figure 1. Sketch of an ultrasonic nebulizer: 1 – piezoelectric Langevin transducer; 2 – emitting concentrator pad; 3 – reflective pad; 4 – piezoceramic elements; 5 – working tool; 6 – technological volume; 7 – jet; 8 – fitting; 9 – sprayed liquid; D1 – diameter of the end of the working tool; D2 – nozzle hole diameter; D3 – internal diameter of the technological volume in the end zone of the working tool; D4 – internal diameter of the technological volume.

The sprayer works as follows. The sprayed liquid, which is under pressure in the technological volume, comes under the influence of ultrasonic vibrations of the working tool. The greatest impact on the liquid occurs in the area (height H) between the end surface of the working tool and the surface of the nozzle. A cavitation zone is formed in this area, and the sprayed liquid (a temporary suspension consisting of the sprayed liquid and formed cavitation bubbles) flows into the hole. Due to hydrodynamic action, the suspension flow breaks up into large droplets.

Entering the external environment, a stream of suspension droplets (primary aerosol) containing cavitation bubbles begins the process of implosion, as a result of which the suspension droplets begin secondary atomization.

The basis of the atomizer design is a piezoelectric Langevin transducer. To increase power, you can use a converter described in [6-7]. A piezoelectric transducer converts electrical energy into the energy of high-intensity mechanical vibrations of ultrasonic frequency. Piezoelectric transducers used in ultrasonic equipment are resonant systems operating at fundamental resonance frequencies. Most often, compound or packet converters (Langevin converters) are used [8].

The total wavelength (considering differences in the propagation speeds of ultrasonic vibrations in the materials of the pads and piezomaterial) of the reflective pad, two piezoelectric elements and the radiating pad corresponds to half the wavelength of the generated vibrations. Figure 2 shows a sketch of the Langevin piezoelectric transducer, obtained from the calculation results, the oscillation shape of the piezoelectric transducer and its photo.



a) b)

c)

Figure 2. Developed piezoelectric transducer: a) sketch of an ultrasonic piezoelectric transducer (1 – radiating patch-concentrator; 2 – reflective pad; 3 – piezoceramic elements; 4 – tightening bolt); b) oscillation shape of the piezoelectric transducer; c) photo.

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The converter consists of a frequency-reducing radiating pad (#1), a reflective frequency-reducing pad (#2), piezoelectric elements (#3) and a tightening bolt (#4). When developing the converter, piezoelectric elements measuring 35x12x6.35, brand APC-841, were used. The piezomaterial used is characterized by a high piezomodulus, high quality factor, low dielectric losses, low hygroscopicity, and relatively high electrical and mechanical strength. Such a converter is compact, has high efficiency, and when using a concentrating working pad, it provides an increase in the oscillation amplitude up to 10 times.

The radiating pad (#1) in the converter is made of titanium alloy (VT5), and the reflective pad (#2) is made of steel (Steel 45). This choice of material ensures an increase in the efficiency of the converter (increase in the transformation ratio) in relation to the wave impedances of the reflective and radiating pads.

To increase the amplitude of oscillations, the radiating pad is made in the form of a concentrator with a radius transition. This half-wave design makes it possible to combine a quarter-wave piezoelectric transducer and a concentrator of mechanical ultrasonic vibrations.

Determination of acoustic and geometric parameters and calculation of the vibration shape of the emitter was carried out using modal analysis in a finite element modeling system (Ansys package).

When carrying out calculations of the piezoelectric transducer and the working tool, data on materials (density, Young's modulus, Poisson's ratio) presented in Table 1 were used.

To calculate and analyze the operation of an ultrasonic emitter experiencing a volumetric stress state, a tetrahedral type of finite element was used. When performing modal analysis, an analysis of the convergence of numerical results for various designs of emitters was carried out. The simulation result was considered satisfactory if it corresponded to a finite element model with a minimum number of finite elements, an increase in which leads to a change in the main values of the design parameters (for example, the natural frequency of vibrations) by no more than 0.2 - 0.5%.

Table 1. Characteristics of materials used in modeling.

#	Element	Material	Young's modulus, E, Pa	Density, ρ, kg/m^3	Poisson's ratio, μ
1	Work tool	Ti Grade6	$12.4*10^{10}$	4500	0.32
2	Radiating pad	AA7075	$7.1*10^{10}$	2800	0.31
3	Piezoceramic ring	APC-841	$7.6*10^{10}$	7600	0.33
4	Reflective overlay	Steel 1045	$2*10^{11}$	7810	0.28

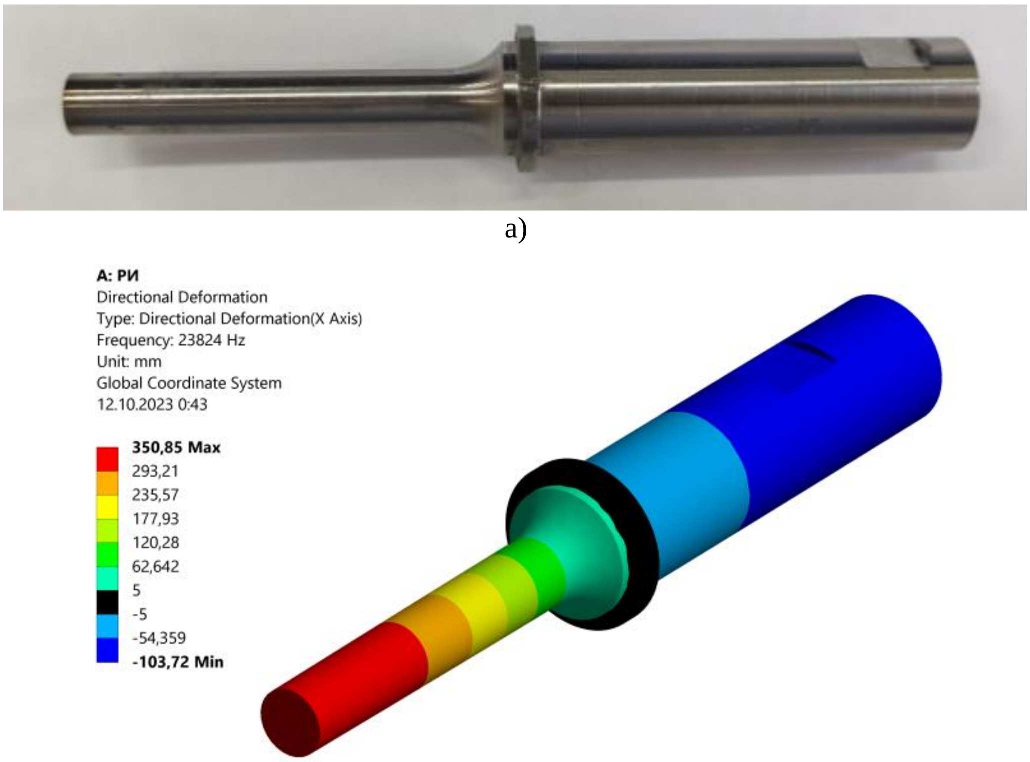
Measurements of the amplitude of mechanical vibrations were carried out using a non-contact vibrometer VM1-5, based on the capacitive method. Duplicate measurements of the oscillation amplitude were also carried out using a displacement indicator.

The measurement results showed that the vibration amplitude of the end surface of the developed piezoelectric transducer was 30 μm.

Analysis of the obtained data indicates the performance of the proposed design of the piezoelectric transducer.

Further research was aimed at developing a working tool.

To increase the amplitude of oscillations, it was proposed to make the working tool in the form of a concentrator with a stepped-radial transition. Figure 3 shows the vibration shape of the working tool obtained from the calculation results and its photo.



a)

b)

Figure 3. Developed working tool: a) photo of an ultrasonic working tool; b) vibration shape of the working tool.

At the current stage of research into the spraying process, a working tool with a flat oscillating end surface has been developed. As can be seen from the calculation results, the mounting flange is located in the node of minimum amplitudes (the zone of minimum amplitudes is indicated in black). Therefore, it is possible to attach the technological volume to this flange.

The use of a tool of this design makes it possible to obtain an additional vibration transformation coefficient (3.5). Titanium alloy VT5, characterized by good wear resistance, was chosen as a material for the manufacture of working tools.

After assembly, measurements of the oscillation amplitude were carried out; it was found that the maximum achievable oscillation amplitude without load was 100 μm, which is sufficient to implement ultrasonic influence on the liquid.

Table 2 presents the technical characteristics and the most important geometric dimensions of the developed sprayer.

Table 2. Technical characteristics of the developed sprayer.

Characteristic	Value
Resonance frequency, kHz	22.5
Maximum amplitude (span) of mechanical vibrations of the working tool (no load), μm	100
Maximum amplitude (span) of mechanical vibrations of the working tool (in liquid at a pressure of 10 bar, determined indirectly by current), μm	76
Power consumption under maximum load, W	250
Diameter of the end of the working tool (D1), mm	8
Nozzle hole diameter (D2), mm	0.7
Inner diameter of the technological volume in the end zone of the working tool (D3), mm	10
Inner diameter of technological volume (D4), mm	16
Inner diameter of fitting (item 8), mm	6
Distance between the end surfaces of the working tool and the nozzle (H), mm	1.5

3. Results and discussion

At the next stage of research, measurements of spraying performance were carried out at different levels of amplitude of oscillations of the end of the working tool and different values of excess fluid pressure. Figure 4 shows the dependence of water spraying performance on pressure at different tool vibration amplitudes.

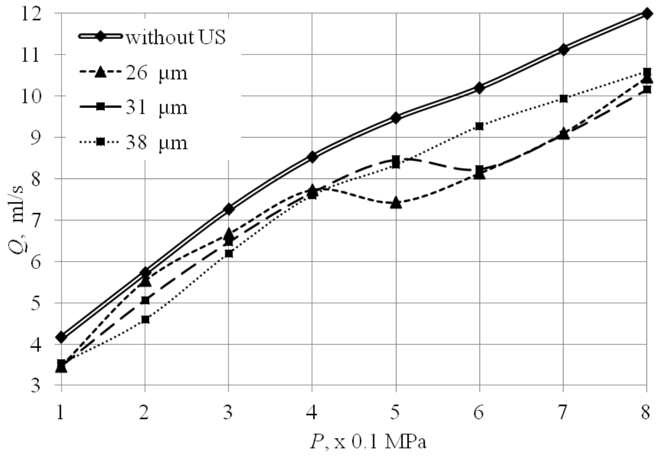


Figure 4. Dependence of water spraying performance (Q) on pressure (P) at different tool vibration amplitudes.

Analysis of the obtained dependencies showed that an increase in pressure leads to an increase in productivity. It was also found that an increase in the amplitude of oscillations leads to a decrease in performance at a set pressure. In addition to this, the graphs show that when the pressure exceeds a certain threshold value, productivity decreases. For example, an increase in pressure from 0.4 MPa to 0.5 MPa with an oscillation amplitude of 26 μm (range 52 μm), productivity decreases from 7.8 ml/s to 7.4 ml/s. This creates an additional noise effect. With the same change in pressure, the spraying performance without ultrasonic influence increases from 8.5 to 9.5 ml/s.

At the next stage of the research, the dispersed composition of the formed aerosol was measured at different pressures, with the amplitude set at 26 μm. Measurements were carried out using a Spraytec system from Malvern Instruments. Figures 5 and 6 show examples of particle size distributions.

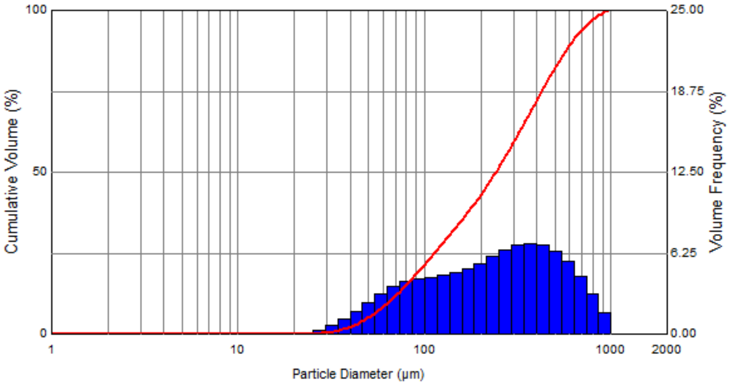


Figure 5. Volumetric particle size distribution (overpressure 0.2 MPa; D32 = 146 μm; A = 26 μm).

Analysis of the resulting distribution showed that at a pressure of 0.2 MPa, two maxima are formed. In this case, the first maximum is associated with the fragmentation of droplets into small ones due to implosion and due to direct ultrasonic spraying. The second maximum (region of large droplets 300 μm in size) is associated with insufficient fragmentation of the primary liquid jet.

When the pressure increases to 0.65 MPa (Figure 6), the largest droplets are not observed, uniform ultrasonic treatment of the entire liquid flow occurs, resulting in the formation of an aerosol with a unimodal distribution.

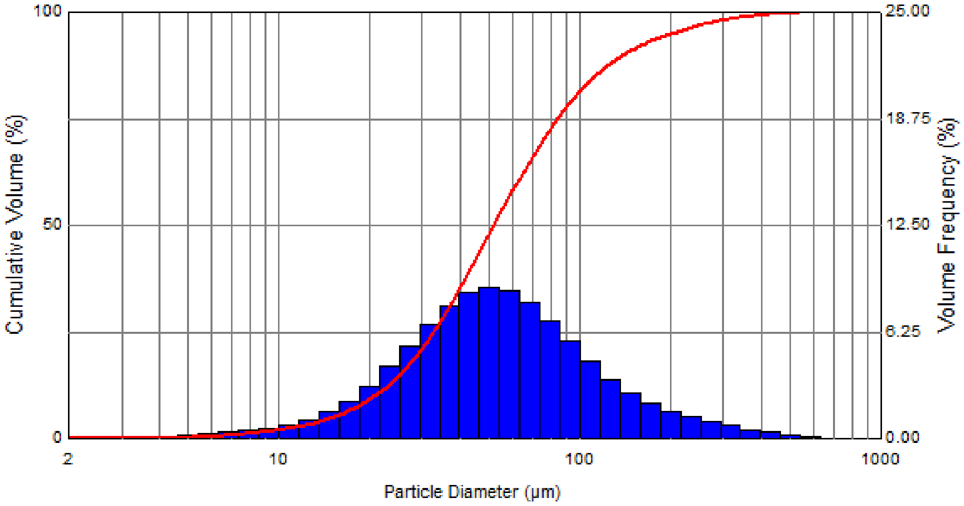


Figure 6. Volumetric particle size distribution (overpressure 0.65 MPa; D32 = 39 μm; A = 26 μm).

Experimental studies of the spraying process at different values of excess pressure and measurements of the dispersed composition made it possible to obtain the dependence of the size of droplets D_{32} on excess pressure (Figure 7).

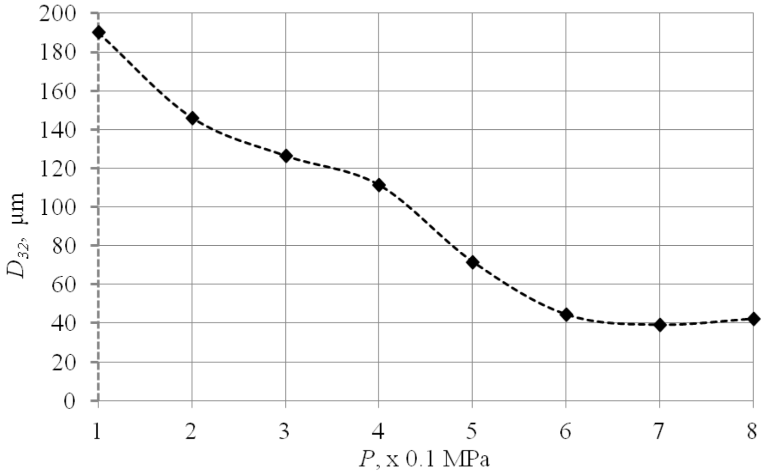


Figure 7. Dependence of particle size D32 on excess pressure (A=26 μm).

Analysis of the data obtained showed that, simultaneously with a slight decrease in spraying productivity, the particle size also decreases. For example, when the pressure changes from 0.4 MPa to 0.5 MPa, the size of the droplets of the formed aerosol sharply decreases from 112 μm to 66 μm.

A decrease in the formed droplets occurs when the pressure increases to 0.7 MPa. A further increase in pressure leads to a slight increase in droplet size, with a proportional increase in spraying productivity.

4. Conclusion

In the process of research, a sprayer was developed based on hydrodynamic and ultrasonic effects on the flow of sprayed liquid. The proposed spraying method makes it possible to increase spraying productivity while reducing the size of aerosol droplets. By establishing optimal conditions, with a nozzle diameter of 0.7 mm, an ultrasonic tool diameter of 8 mm and an excess pressure of the sprayed liquid of 0.7 MPa, the atomizer provides a productivity of 9 ml/s and forms an aerosol with droplet sizes D_{32} = 40 μm. This is primarily due to the establishment of the optimal operating mode and conditions in the cavitation zone, which make it possible to ensure the highest quantitative concentration of cavitation bubbles. Due to this, upon exiting the nozzle, further atomization occurs due to the implosion process, because of which the particle sizes are significantly reduced.

Acknowledgements

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