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Calculation of the surface shape of an ultrasonic atomizer to form a spray torch of the required shape

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Abstract. The article presents a calculation method for the shape of the ultrasonic atomizer surface. The parameters influencing the shape of the spray torch and its performance are considered. Ultrasonic emitters are manufactured according to the obtained calculation formulas and their main technical characteristics are obtained. The developed calculation method allows creating multifunctional ultrasonic atomizers capable of solving various technological problems.

1 Introduction

Ultrasonic atomization is an important technology with a wide range of applications in various fields, such as medical equipment, thin-film coating production, cooling systems, agriculture, etc. [1].

The operating principle of an ultrasonic atomizer is based on the excitation of high-frequency oscillations of the liquid surface [2], resulting in the formation of capillary waves and cavitation bubbles [3]. High oscillation frequency (above 20 kHz) leads to the destruction of the liquid into droplets under the action of inertial forces, surface tension and vibrations. It is important to note that with ultrasonic atomization, droplets are formed more uniformly and smaller than with mechanical atomization methods, which is especially valuable for thin-film coatings and biomedical aerosols [4, 5].

Ultrasonic atomizers have different designs of emitters: flat-surface atomizers, conical atomizers, cylindrical atomizers.

The purpose of this article is to develop a method for calculating the shape of the emitter's spray surface to increase the process speed at various parameters of the atomized liquid.

2 Calculation stages

The occurrence of the cavitation phenomenon causes the appearance of inextricably linked shock waves, which, when certain conditions are met (layer thickness, viscosity and surface

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tension of the liquid, amplitude of the ultrasonic effect), lead to the formation of surface phenomena at the interface between the liquid and the gas medium - capillary waves.

The design of a liquid spray emitter includes the following main calculation stages:

1) determination of the spray surface area based on the specific spray productivity:

$$\Pi = VfN_S = a\frac{\lambda^2 A}{2\pi}\left(\frac{\pi^2}{2}-2\right)fN_S, \tag{1}$$

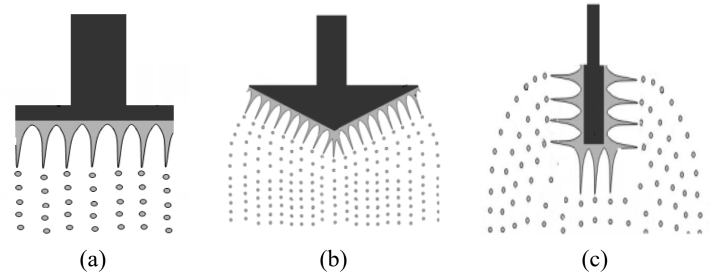
where V is the volume of sprayed droplets from one capillary wave; f is the oscillation frequency of the spray surface; a is the correction factor taking into account the fraction of the capillary wave volume that breaks up into droplets; λ is the length of the capillary wave; A is the amplitude of the capillary wave; NS is the number of capillary waves per unit surface area, which is taken to be equal to the number of cavitation bubbles;

2) determining the angle of inclination γ of the generatrix of the conical spray surface for a given spray diameter d at a distance h from the sprayer;

3) determining the number and location of holes for supplying liquid to the spray surface.

2.1 Determining the angle at the top of the spray surface

The angle at the top of the spray surface (spray angle) is the most important parameter affecting the characteristics of the aerosol spray shape. Figure 1 shows three possible shapes of the ultrasonic spray surface depending on the spray angle.


(a) (b) (c)

a) flat; b) conical; c) cylindrical

Fig. 1. Sprayer surface shapes.

The variants presented in Figures 1a and 1c are extreme cases of the radiating surface. In the case of a flat surface, the spray angle is 180°, and the aerosol plume formed by such a spray surface will have the minimum possible width, approximately equal to the diameter of the spray surface. When using a cylindrical spray surface, the droplet detaches from the spray surface in the direction perpendicular to the direction of gravity, and, accordingly, the formed plume has the maximum width for sprayers of the type under consideration. The most common case in practice with a conical spray surface is intermediate, and, therefore, the formed spray plume lies within the limits determined by the cases presented in Figures 1a and 1c.

To solve the problem of finding the spray angle γ for a given spray plume diameter, we will consider a spray plume formation model based on assumptions.

1. Each drop is considered as a small solid spherical body with a mass m and an initial velocity *v*.

2. As the drop falls, it is acted upon by gravity and air resistance. The latter will be equal to $\rho S v^2 C_D(M)$ – the formula for the air resistance force, where ρ is the air density; *S* is the cross-sectional area; *v* is the speed of movement; and $C_D(M)$ is a dimensionless function of the Mach number (equal to the ratio of the drop speed to the speed of sound in the medium in which the drop moves), called the drag coefficient.

For ease of understanding the solution to the problem, Figure 2 schematically illustrates the forces acting on the drop of the sprayed liquid.

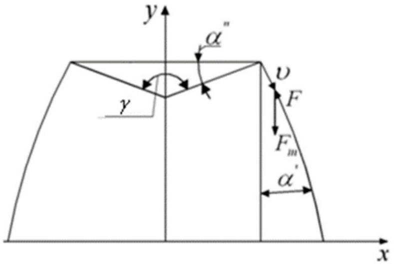


Fig. 2. The system of forces acting on a drop of liquid after it separates from the liquid film covering the spray surface.

Let us assume that at the initial moment of time the drop moves at some angle to the horizon, since $\alpha'' = \left(90 - \frac{\gamma}{2}\right)$, then $\alpha' = 90 - (90 - \alpha'') = \left(90 - \frac{\gamma}{2}\right)$, then the projection of the velocities on the axes will look like this [6]:

$$\upsilon_x = \upsilon \cdot sin\,\alpha'. \tag{2}$$

$$\upsilon_y = \upsilon \cdot cos\,\alpha'. \tag{3}$$

Let us write the equation of equilibrium of forces at an arbitrary moment of time:

$$ma = F + F_m. \tag{4}$$

The system of equations taking into account the projections will have the following form:

$$\begin{gathered} x\colon\ ma_x\,sin\,\alpha' = -F\,sin\,\alpha'; \\ y\colon\ ma_y\,cos\,\alpha' = F\,cos\,\alpha' + F_m. \end{gathered} \tag{5}$$

The differential equations describing the flight of the drop for the adopted model will have the following form:

$$\begin{gathered} x\colon\ \frac{\partial^2}{\partial t^2}x(t)m \cdot sin\,\alpha' = \rho S^2 \left(\frac{\partial}{\partial t}x(t)\right)^2 C_D(M)\,sin\,\alpha'; \\ y\colon\ -\frac{\partial^2}{\partial t^2}y(t)m \cdot cos\,\alpha' = \rho S^2 \left(\frac{\partial}{\partial t}y(t)\right)^2 C_D(M) \cdot cos\,\alpha' - mg. \end{gathered} \tag{6}$$

Since the first derivative of the path with respect to time is the speed of movement, the differential equations will take the following form:

$$\begin{gathered} x\colon\ \frac{\partial}{\partial t}\upsilon_x(t)m \cdot sin\,\alpha' = -\rho S^2(\upsilon_x(t))^2 C_D(M) \cdot sin\,\alpha'; \\ y\colon\ -\frac{\partial}{\partial t}\upsilon_y(t)m \cdot cos\,\alpha' = \rho S^2\left(\upsilon_y(t)\right)^2 C_D(M) \cdot cos\,\alpha' - mg. \end{gathered} \tag{7}$$

When the drop moves at an angle, the initial angle is equal to α', but as the drop moves, this angle will change according to the following law:

$$\alpha' = arctg\left(\frac{\upsilon_x}{\upsilon_y}\right). \tag{8}$$

Figure 3 shows the obtained dependence of the increment of the spray torch radius on the angle of the atomizer at a distance of one meter at different values of the oscillation frequency.

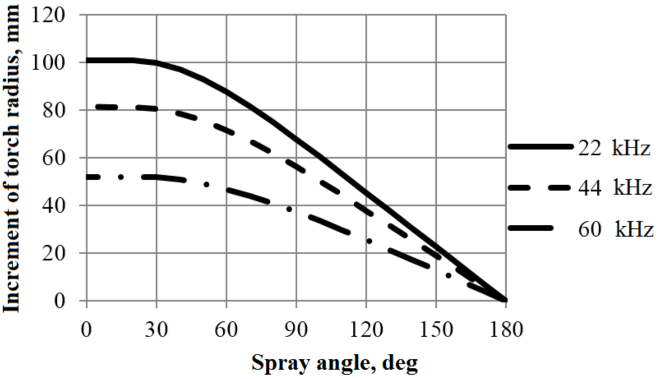


Fig. 3. Dependence of the increment of the spray torch radius on the nozzle angle.

The graph shows that the relative increase in the spray cone diameter is directly proportional to the spray angle γ. However, the dependence is nonlinear and at spray angles less than 60°, there is no further increase in the spray cone width. Therefore, when designing ultrasonic sprayers, the angle should be selected from the range of 60°–180°.

2.2 Determining the number and location of holes

2.2.1 Determining the liquid spreading area on the spray surface

The location and number of holes on the spray surface are determined from the condition of ensuring its uniform coverage with a layer of sprayed liquid. Since the theoretical determination of the radius of the circle R_0, along which the sprayed liquid spreads under the action of ultrasonic vibrations, is a complex task, it was decided to conduct a series of experiments aimed at determining this value. During the experiments, the liquid feed rate was discretely changed in 1 ml increments. The results obtained are shown in Figure 4.

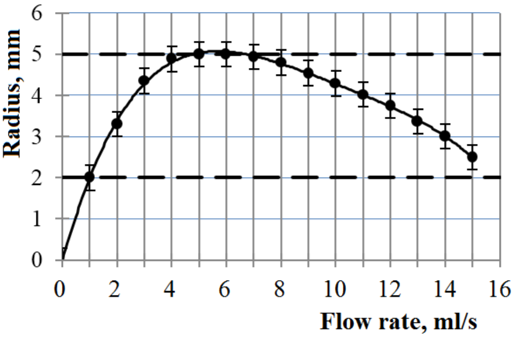


Fig. 4. Dependence of the liquid spreading radius R_0 on the productivity of its supply to the spray surface.

To determine the liquid spreading radius R_0 at other angles at the apex of the spray surface angle γ, the obtained values must be multiplied by the cosine value γ/2.

2.2.2 Determining the number and location of holes for supplying liquid to the spray surface

The liquid flowing out of the central channel will provide coverage of the spray surface at a distance not exceeding R_0 from the central hole (Figure 5).

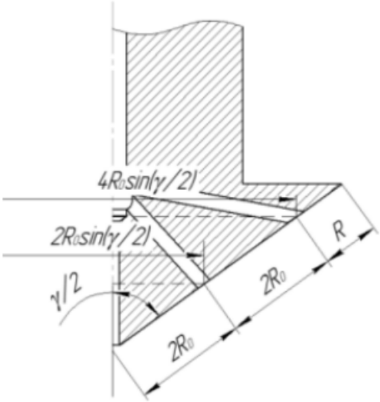


Fig. 5. Spray surface.

To cover the remaining area of the spray surface with liquid, it is necessary to make these holes at a distance of $2R_0$ from each other along the cone generatrix. In this case, the most rational is to place additional holes (in addition to the central hole made at the top of the cone) on the circles.

The radius of these circles will increase by $2R_0\, sin\frac{\gamma}{2}$ with each new circle located further from the center of the cone. The number of circles is calculated so that they are located at a distance of $2R_0$ from each other and at a distance of R_0 from the outer edge. With a known radius of the spray surface R, the length of the cone generatrix will be equal to $N = \frac{R}{sin\frac{\gamma}{2}}$. Then the number of circles that can be placed along such a cone generatrix will be equal to

$$N = \frac{\frac{R}{sin\frac{\gamma}{2}} - R_0}{2R_0} \tag{9}$$

or, moving to a common denominator:

$$N = \frac{R - R_0\, sin\frac{\gamma}{2}}{2R_0\, sin\frac{\gamma}{2}}. \tag{10}$$

If the obtained value is not an integer, then it is rounded to the nearest integer value and the value of R_0 is specified, $\frac{R}{sin\frac{\gamma}{2}} = N \cdot 2R_0 + R_0$, therefore:

$$R_0 = \frac{R}{(2N+1)\, sin\frac{\gamma}{2}}. \tag{11}$$

The radius of each of the circles will be equal to

$$R_i = 2iR_0\, sin\frac{\gamma}{2}, \tag{12}$$

where $i = 0 \dots N$ is the circle number.

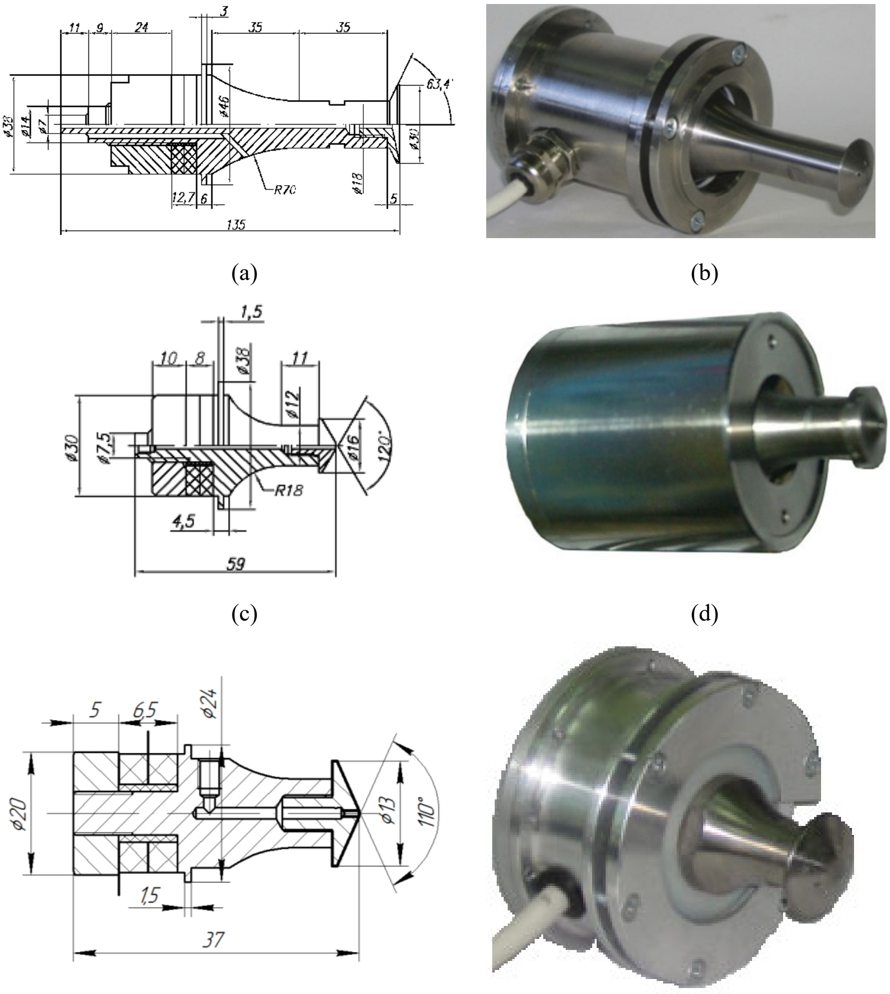
The centers of the holes of the channels for supplying liquid on each of the circles are also uniformly located at a distance of $2R_0$ from each other along the length of the circle. The number of channels on each circle is equal to:

$$K = \frac{2\pi i \cdot 2R_0\, sin\frac{\gamma}{2}}{2R_0} = 2\pi i\, sin\frac{\gamma}{2}, \tag{13}$$

3 Forms of ultrasonic emitters

Thus, all the necessary mathematical tools for calculating the ultrasonic vibrating system for liquid atomization were developed.

Based on the results obtained, three types of ultrasonic vibrating systems with resonant frequencies of 22 kHz, 44 kHz and 60 kHz were developed. Figure 6 shows the developed oscillatory systems for liquid atomization with the main design dimensions indicated.



(a) (b)

(c) (d)

(e) (f)

a), b) – frequency 22 kHz; c), d) – frequency 44 kHz; e), f) – frequency 60 kHz

Fig. 6. Designs of piezoelectric half-wave ultrasonic oscillatory systems for liquid atomization.

The reflective pad material was made of 45 steel; APC-841 piezoelectric element of various design sizes; concentrator material – VT-14, VT-6 titanium alloys. Direct ultrasonic impact on the sprayed liquid is achieved through the radiating surface of the replaceable working tool of the ultrasonic spraying system (spraying surface). The use of replaceable working tools of different shapes and radiating surface areas allows creating spray torches of various shapes (flat, round, of various geometric sizes) and with different density distributions of the sprayed liquid inside the torch, which allows creating multifunctional ultrasonic sprayers capable of solving various technological problems.

Preliminary studies of the characteristics of the developed ultrasonic spraying systems have shown that they provide the formation of droplets with an average diameter of 40 µm for liquids with a viscosity of up to 30 mPa·s.

4 Conclusion

The article presents formulas for calculating the shape of the ultrasonic atomizer surface. The parameters influencing the shape of the spray torch and its performance are considered. Ultrasonic atomizers have been created that provide the formation of droplets with an average diameter of 40 µm for liquids with a viscosity of up to 30 mPa·s.

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References

1. A.M. Al-Jumaily, A. Meshkinzar, Advances in Acoustics and Vibration **2017(1)**, 7861726 (2017).
2. S.V. Sancheti, P.R. Gogate, Ultrason. Sonochem. **36**, 527-543 (2017).
3. M. Ashokkumar, Ultrason. Sonochem. **18(4)**, 864-872 (2011).
4. S. Nii, K. Matsuura, T. Fukazu, M. Toki, F. Kawaizumi, Chem. Eng. Res. Des. **84**, 412-415 (2006).
5. J.C. Simon, O.A. Sapozhnikov, V.A. Khokhlova, L.A. Crum, M.R. Bailey, J. Fluid Mech. **766**, 129-146 (2015).
6. A.V. Shalunov, V.N. Khmelev, A.V. Shalunova, *Development of Design Procedure of Liquid Media Dispenser for the Atomizing Drier International Conference and Seminar on Micro A Nanotechnologies and Electron Devices* in: EDM'2009: Conference Proceedings pp. 269–273 (Novosibirsk NSTU, 2009).