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POSSIBILITIES OF INCREASING THE PRODUCTIVITY OF THE ULTRASONIC ATOMISER

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ABSTRACT

Ultrasonic thin film atomisation produces a quality monodisperse aerosol with a dispersity of up to 5 ... 30 µm at an ultrasonic frequency of 22 ... 66 kHz. Obtained monodisperse aerosol can be used in many technological processes, especially when the possibility of using other methods of atomization is limited by the properties of the liquid. Such technological processes are widely used in mechanical engineering, chemical industry, medicine and agriculture as part of mechatronic automation systems and many other industries.

INTRODUCTION

In today's world there are many different technological processes that require automated mechatronic systems. A large number of these use liquid aerosols. These are technological processes in medicine, agriculture, machine building, engine building, instrumentation and chemical industry. The efficiency and quality of these technological processes depend to a large extent on the parameters of the liquid aerosol, used, and the possibility of controlling them.

For example, in the process of applying antireflective coating on silicon wafers in the production of light-sensitive batteries in the instrumentation industry, high efficiency can be achieved at a dispersion of the aerosol of 5 ... 15 µm [1, 2].

In the food processing industry, the sausage production process requires constant moistening of the product. This is preferably achieved with an aerosol dispersibility that saturates the thermal chamber, within the range of 10 ... 30 µm.

In the medical device industry, when creating, for example, artificial microclimate chambers for the care of the sick and the frail, there is a need to saturate the closed volume with a drug aerosol with a dispersion of 0.5 ... 5 µm. Injection or evaporation of the aerosol into the volume is not permissible, as constant pressure and temperature must be maintained [2, 3].

In agriculture, liquid aerosol is used extensively in modern greenhouse facilities to produce the required atmospheric humidity. However, the use of aerosol with a droplet diameter of more than 300 ... 400 microns is inadmissible, because large liquid droplets deposited on the leaf surface, under the condition of powerful artificial greenhouse lighting, turn into optical focusing systems and damage the leaves, burning them [3].

In these cases we are talking about aerosol production with a capacity of up to 100 ml/min. But there are many technological processes in mechanical engineering, chemical and petrochemical industries, in agriculture, where there is a need for aerosol with droplet diameter of 500 µm and more at capacities up to 6000 l/h.

The analysis shows that the current state of the industry requires automated mechatronic systems, in which liquid atomisation devices are required both to provide the necessary dispersity, performance and shape of the aerosol plume, and the requirements for fast electronic control of them.

EXPOSITION

The most efficient atomization method, which for the most part satisfies the requirements for automated mechatronic systems, is ultrasonic thin film atomization. However, in order to increase the productivity of processes using this atomization method, the problem of a uniform supply of liquid to the entire atomization surface must be solved.

So, to obtain high quality aerosol at maximum dispersant capacity it is necessary to ensure complete coverage of vibrating surface with liquid layer and to ensure stability of its thickness. Changing the angle of inclination of the atomization surface can reduce parasitic coagulation of aerosol in the plume, which will narrow the limits of dispersion of aerosol droplet diameters.

Existing calculation methods for ultrasonic resonant actuators of various acoustic circuits [4] make it possible to calculate the longitudinal dimensions of the actuator components. In order to calculate the dispersant surface, it is necessary to specify the type of liquid, the average diameter of the aerosol droplet and the desired performance of the dispersant. Based on this, an engineering method was

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developed to calculate the design parameters of the atomizing surface of ultrasonic dispersants which implement the thin film atomizing method with the introduction of acoustic energy from the liquid side [5].

It is recommended that the capillary wave length arising on the surface of the thin layer of liquid that covers the vibrating surface of the dispersant should be calculated according to formula [6]

$$\lambda_k = \sqrt[3]{\frac{8\pi\sigma}{\rho f^2}}, \quad (1)$$

where σ – the surface tension coefficient of the liquid atomised; ρ – fluid density; f – acoustic frequency.

According to the investigated regularities of the ultrasonic atomisation process [6] there is a correlation between the average diameter of the aerosol droplets d_k and the capillary wavelength λ_k at the surface of the liquid layer

$$d_k = \alpha\lambda_k,$$

where α – sound energy absorption coefficient of a viscous thermal conductive medium, $\alpha \approx 0.3$.

Then the average diameter of the aerosol droplet, which is related to the rheological properties of the liquid atomised, and the frequency of capillary oscillations, will be determined by

$$d_k = \alpha\sqrt[3]{\frac{8\pi\sigma}{\rho f_k^2}}. \quad (2)$$

Or the frequency of acoustic oscillation at which the desired aerosol dispersion is achieved, is determined by

$$f_k = \sqrt{\frac{\alpha^3 8\pi\sigma}{d_k^3\rho}}.$$

In accordance with the Faraday effect, the resonant frequency of the f excitation of the dispersant's acoustic system is defined as $f = 2f_k$.

The acoustic dimensions of the disperser's constituent parts must therefore be calculated with the resonance frequency in mind, using known methods.

$$f_k = \frac{1}{2}\sqrt{\frac{\alpha^3 8\pi\sigma}{d_k^3\rho}} \quad (3)$$

Based on the wave hypothesis of ultrasonic atomisation [7], assume that with each formation of a standing capillary wave crest a single aerosol droplet of a constant diameter d_k will necessarily separate at the final stage. In this case during the first time interval $0.5T_k$ (T_k - oscillation period of capillary wave) two ridges and two troughs are formed on the area which is defined as $S = \lambda_k^2$. Correspondingly we get two drops of aerosol. In the next interval $0.5T_k$ the ridges and troughs are swapped and two aerosol droplets are produced again [6].

In this way, a volume of liquid will be atomized T_k from the area over a period of time:

$$V_s = \frac{8}{3}\pi d_k^3. \quad (4)$$

Then the flow rate of ultrasonic thin film atomisation from the area S can be determined by

$$Q_S = \frac{V_S}{T_k},$$

or

$$Q_S = V_S f_k. \quad (5)$$

Considering the total capacity Q of the dispersant, the number of planes required on the atomization surface S covered by the thin liquid layer can be determined:

$$n_S = \frac{Q}{Q_S}, \quad (6)$$

which means the surface area of the atomization surface will be:

$$S_{pn} = n_S S. \quad (7)$$

If the atomisation surface is flat, resulting in a dense, narrow aerosol plume (Figure 1) [4], the diameter d_{pn} of the dispersant atomisation surface will be

$$d_{pn} = 2\sqrt{\frac{S_{pn}}{\pi}}.$$

or given relations (1), (3) to (7):

$$d_{pn} = \frac{1}{\pi}\sqrt[3]{\frac{8\pi\sigma}{\rho f^2}} \cdot \sqrt{\frac{3Q}{d_k^3\sqrt{\frac{8\alpha^3\pi\sigma}{d_k^3\rho}}}}.$$

Fig. 1. Narrow, dense aerosol plume during ultrasonic atomization

If, on the other hand, the atomization surface of the dispersant is tapered to produce an extended aerosol plume (Figure 2) [4], its dimensions are related by

$$d_{pn} = \frac{2S_{pn}}{\pi h_{кон}}$$

where $h_{кон}$ – taper height of atomization surface.

Or given relations (1), (3)-(7):

$$d_{pn} = \frac{3Q\sqrt{\left(\frac{8\pi\sigma}{\rho f^2}\right)^2}}{2\pi^2 h_{кон} d_k^2 \sqrt{\frac{8\alpha^3\pi\sigma}{d_k^3\rho}}}$$

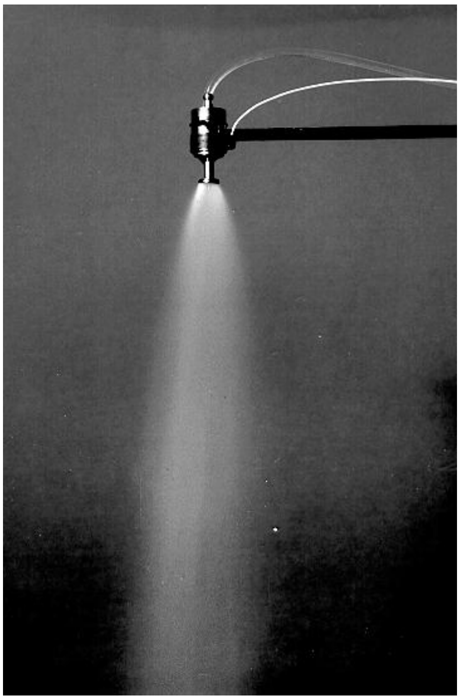

Fig. 2. Extended aerosol plume during ultrasonic atomization

In the case of a cone-shaped atomization surface in order to obtain an umbrella aerosol plume (Fig. 3) [4], the surface dimensions are defined by the following relationship:

$$S_{pn} = \frac{\pi}{2}\left[\frac{1}{2}\left(d_{pn}^2 + d_{mp.ш}^2\right) + \left(d_{pn} + d_{mp.ш}\right)\cdot l\right],$$

where $d_{mp.ш.}$ – diameter of the degree of small area of the oscillating speed transformer; l – cone generatrix.

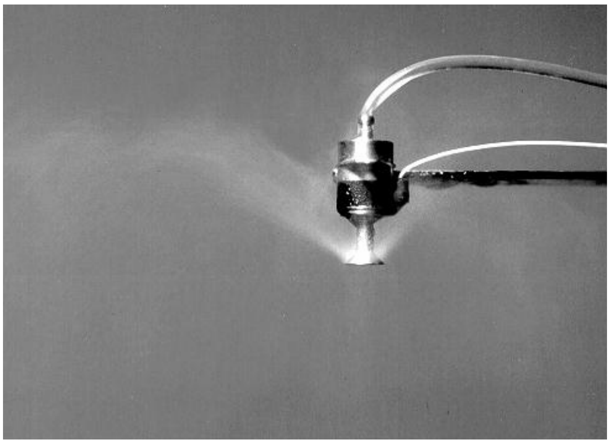

Fig. 3. Umbrella-shaped aerosol plume during ultrasonic atomisation

The supply of liquid to the atomising surface can be done in various ways [4]. The most common is the use of a system of orifices, which feed the liquid from a central channel, made in the axis of the oscillating speed transformer, to the atomising surface. The number of holes varies from one to several. In the case of a large atomisation surface area, several holes are used in order to maintain uniformity of surface wetting. Hole diameters of 0,7 ... 1 mm in diameter. In the presence of cavitation in ultrasonic atomization clogging of such holes is unlikely. In high capacity ultrasonic dispersants an intermediate chamber (Fig. 4) is used in order to achieve equal conductivity of holes [8]

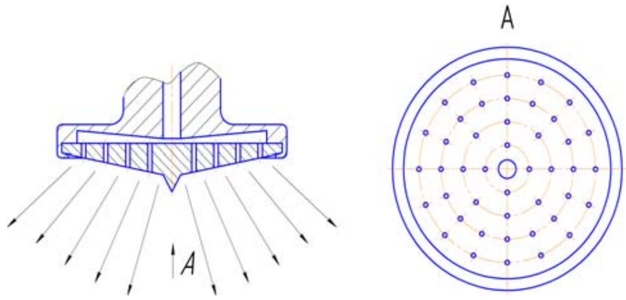

Fig. 4. Large capacity atomisation surface diagram

The fluid flow rate through a single inlet opening can be written as

$$Q_{отв} = \frac{1}{4}\mu\pi d_{отв}^2\sqrt{2gH},$$

where H – head; $d_{отв}$ – the diameter of the hole that brings in the liquid; μ – discharge coefficient.

The number of holes required to achieve the required output is then

$$n_{отв} = \frac{Q}{Q_{отв}}.$$

The holes are structurally placed along the spraying surface, ensuring that the surface is evenly wetted by the liquid.

If the diameter of the atomisation surface is larger than the diameter of the output end of the oscillating speed transformer, it becomes necessary to adjust the acoustic dimensions of the transformer to ensure a constant resonance frequency.

In case of application of the most technological step transformer of vibration velocity, according to the method of calculation of ultrasonic dispersants [4], the degree length of the smaller area of the vibration velocity transformer (Fig. 5) is calculated according to the dependence

$$a_1 = \frac{c_1}{\omega} arct \frac{E_1 S_1 c_2}{E_2 S_2 c_1 tg \frac{\omega}{c_2} b_{цил}} \quad (8)$$

where E_1 and E_2 – tensile moduli of the transformer material of the vibrating speed and the atomisation surface; c_1 and c_2 – speed of sound in the respective materials; ω – circular frequency of the ultrasonic vibrations; $b_{цил}$, S_2 – height and area of equivalent cylinder, which corresponds to the mass of atomizing surface.

The construction weight of the atomisation surface is defined in general terms by the relationship

$$m_1 = \frac{E_2}{c_2^2} V_{пов.р.} + m_{ш.р.},$$

where $V_{пов.р.}$ – atomisation surface design volume; $m_{ш.р.}$ – the mass of the liquid layer on the atomisation surface.

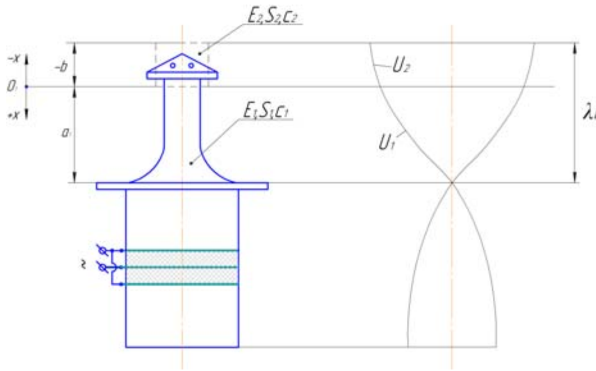

Fig. 5. Calculation diagram of a half-wave ultrasonic dispersant with stepped oscillation speed transformer

The mass of the cylinder equivalent in mass of the spraying surface design elements is determined as

$$m = \frac{E_1}{c_1^2} S_2 b_{цил} .$$

The height of the equivalent cylinder will then be

$$b_{цил} = \frac{\frac{E_2}{c_2^2} V_{пов.р.} + m_{ш.р.}}{\frac{E_1}{c_1^2} S_2} .$$

The resulting value for the height of the equivalent cylinder is used in calculations using formula (8).

Using this engineering methodology for calculating the ultrasonic dispersant, the acoustic dimensions of the dispersant elements and the atomisation surface can be obtained to give the required aerosol output and dispersity for the required shape of the atomisation plume [5].

Looking at real-world examples, normally the dispersants (Fig. 6) used to realise ultrasonic thin film atomisation provide capacities of up to 0.7 l/min. Many processes, however, require considerably higher capacities. In turn, productivity depends on surface tension of liquid, frequency and amplitude of oscillation of atomization surface, as well as its area. As already shown, an increase in amplitude of vibration initially results in higher productivity, but when the level of cavitation developed in the liquid is reached, the mechanism of cavitation sparging is added to the thin film atomization mechanism, which negatively influences the dispersion. Accordingly, the effect of the frequency and amplitude of atomizing surface oscillations on the output is limited by the dispersion requirements of the aerosol. Today, in most cases, designs are rationalised in order to reduce acoustic losses and electrical voltages, led to piezoceramic elements.

In fact, the only effective way to increase output is to increase the dispersant's atomisation surface, which vibrates and is coated with a thin layer of liquid. Typically, the dispersant is a rod packet piezoceramic transducer, via an oscillating speed transformer connected to a disc. It is the disc that will act as the atomisation surface. Accordingly, an increase in the area of the disc will result in an increase in the atomisation surface. However, an increase in the area of the normally vibrating surface is centrally excited, resulting in a bending oscillation of the surface [9]. The bending oscillations of the atomizing surface will of course lead to the appearance of nodal zones in which the amplitude of oscillations will be minimal, which will consequently make it impossible to form capillary waves on the vibrating liquid surface, the breakdown of which generates fine aerosol [4]. That is, there will be no atomisation at the nodal point of the vibrating surface (Figure 7). If it is atomisation, e.g. of water or aqueous solutions, then liquid will collect in the nodal zones. But if atomizing molten metal to produce a fine metal powder, this problem will result in solidification of the metal in these problem areas and failure of the dispersant. As you can see, the performance of rod dispersators is determined by the design of the element that acts as the atomization surface.

An example of an alternative design is the use of a cylindrical tubular atomisation surface which is excited on a radial vibration mode [10].

With purely radial oscillation there will be no nodal zones and this allows the capacity of the dispersators to be increased to 4 ... 5 l/min. However, practice shows that it is very difficult to keep the modulus of purely radial oscillation and similar dispersants cannot achieve monodispersity of the aerosol.

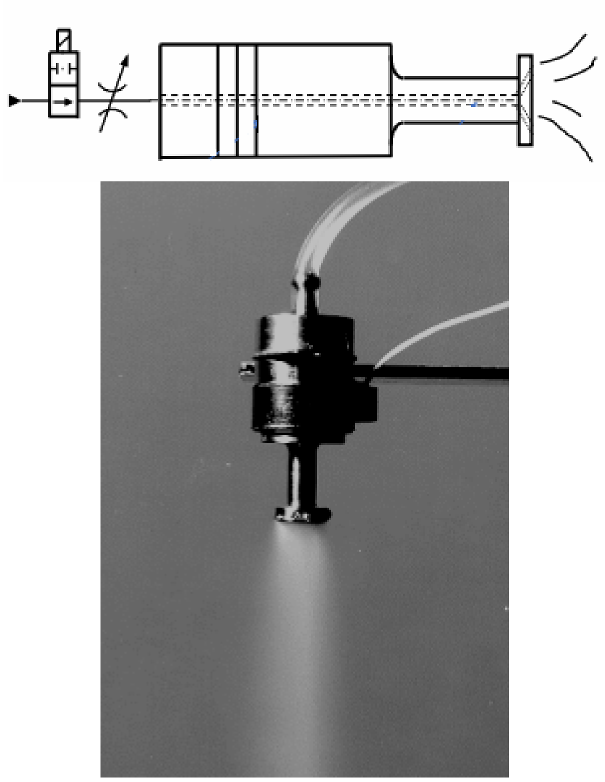

Fig. 6. Ultrasonic dispersant with flat surface, atomizes (power consumption 20 W, capacity 0.07 l/min, resonance frequency 66 kHz)

Fig. 7. Ultrasonic dispersant with a tubular atomisation surface that is excited by the radial-bending vibration mode

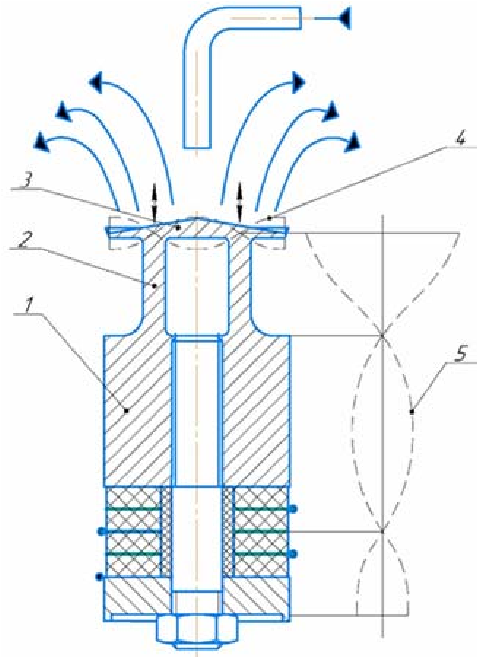

Fig. 8. High performance ultrasonic dispersant with applied axial excitation oscillations in the nodal area of the atomisation surface bending oscillations

Quite interesting is a technical solution proposed by the authors, which provides applications of vibrations normal to the atomization surface, excite the atomization surface not in the zones of bundles, but in the nodal zones (Fig. 8) [11]. This results in a substantial increase in vibrating surface area able to realize atomization process in thin layer. In the proposed solution the outlet end of the vibrating speed transformer 1 is a tubular shape 2, the average diameter of which is equal to the diameter of the nodal line 4 of cylindrical atomization surface 3 which carries out the bending vibrations which are excited by longitudinal vibrations of the piezoelectric transducer. As the atomization surface according to the acoustic scheme is placed in the beam of longitudinal oscillations wave 5 the nodal area of cylindrical atomization surface will carry out longitudinal oscillations with the amplitude sufficient for realization of ultrasonic atomization in thin layer.

As we can see, the given design differs not only in excitation of atomization surface, but also in design of oscillating velocity transformer. Experimental testing of the proposed technical solution confirmed the receipt of high-quality monodisperse aerosol with a capacity of 0.8 l/min at a power consumption of 200 W at a resonant frequency of 33 kHz.

CONCLUSION

An engineering methodology for calculating the design parameters of an ultrasonic dispersant for spraying a liquid in a thin layer, which is created on the normally vibrating end surface of an oscillating speed transformer, is presented. This engineering methodology allows to calculate the acoustic dimensions of the dispersant components by specifying the acoustic scheme, the materials used, the type of piezoceramics, the dispersity of the aerosol and the productivity.

It has been found that the most feasible way to increase the performance of ultrasonic dispersants is to increase the atomisation surface. Increasing the growth of the atomisation surface is in turn limited by the occurrence of stiffening oscillations in the vibrating surface resulting in oscillation nodes in which atomisation is not present. Possible ways of reducing the effect of stiffening oscillations or preventing their occurrence are either by changing to tubular atomisation surfaces or by changing the excitation points of cylindrical atomisers.

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