Efficiency Increase of the Processes by the Optimization of the Ultrasonic Vibrating System Consisting of Half-Wave Modules of Variable Cross-Section

Vladimir N. Khmelev, Sergey V. Levin, Sergey N. Tsyganok, Sergey S. Khmelev

Biysk Technological Institute (branch) of Altay State Technical University after I.I. Polzunov

***Abstract* – In this paper the tendencies, which let to create and apply piezoelectric tranducers with enlarged radiation surface in order to increase the efficiency of ultrasonic technological devices, are analyzed.**

I. INTRODUCTION

INTENSIFICATION of chemical processes with the help of high-intensity ultrasonic vibrations is one of the perspective lines of development of modern chemical industry.

Among real achievements of ultrasonic technologies nowadays there is acceleration in thousands of times of extraction, dissolution, emulsification, dispersion, increase of yield of useful substances in 10...50% during the extraction, obtaining of materials with new unique properties such as sterility, nanodimension, stability of emulsions, etc.

At the realization of processes in liquid and liquid-dispersed media maximum efficiency of the proceses is provided at the intensity of ultrasonic influence in $1\times10^5…1.5\times10^5$ W/m^2 (10…15 W/cm^2), i.e. at the realization of developed cavitation mode. The area of propagation of cavitation influence (the zone of developed cavitation) is limited by attenuation of propagated vibrations in viscous liquids and changes of wave impedance of cavitating liquid (practically up to wave resistance of gas medium) near the radiating surface, which restricts the output of energy of ultrasonic vibrations from the radiator. For these reasons the amount of simultaneously processed medium is limeted, that makes impossible to use the ultrasonic technologies in industrial scale production.

As the efficiency increase is possible only due to the growth of energy of entered ultrasonic vibrations in the mode of developed cavitation ($1\times10^5…1.5\times10^5$ W/m^2), it is necessary to develop and apply in industry the piezoelectric vibrating systems with enlarged no less than in 5...10 times area of the radiating surface (up to 3×10^{-2} m^2 and more), which are able to provide simultaneous processing of liquid media in the volume of no less than 0.1…0.3 m^3.

II. PROBLEM DEFINITION

The simplest technical solution is the designing of the ultrasonic radiators made by series connection of several half-wave modules in the single radiator [1].

At series connection of the half-wave modules in length to enlarge the radiating surface it is the most effective to apply half-wave modules of variable cross-section consisting of cylindrical parts of different diameter connected with each other by the radial junction [2].

Unfortunately, at the designing of many half-wave radiators with the series connection of half-wave modules there are some problems to be solved:

- providing of maximum effective processing in the whole volume due to the optimization of the construction;
- providing of even radiation of ultrasonic vibrations from the each of half-wave modules;
- designing and optimization of the piezoelectric transducers of increased power, which are able to provide required parameters of the radiation from the surface of the developed radiators.

Thus the first and second tasks included the development of the construction arrangement of the radiator can be solved by the creation of the radiator model consisting of separate half-wave modules and on the base of the analysis of the model to reveal the optimum construction arrangement, at which maximum even ultrasonic processing of liquid in all the volume is provided.

The third task is the design of the piezoelectric transducer uniting the power of separate piezoelectric elements.

III. MULTI HALF-WAVE VIBRATING SYSTEM

The solution of the first task is related to rational series connection of the half-wave modules of the optimum form.

The design of the working tools of such type is based on the creation of the first single element of the waveguide with the length, which equals to half of the wave length of longitudunal vibrations in the module material. The example of such element of the waveguide is shown in Fig. 1.

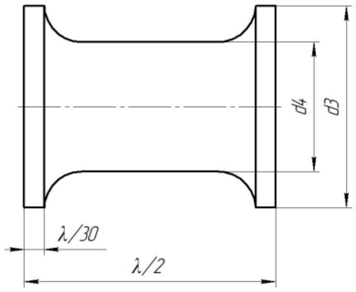
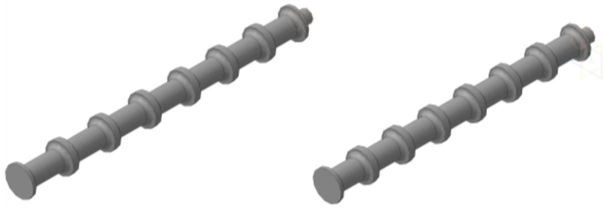


Fig. 1. The half-wave element of the waveguide

The thickness of the asperities located in the antinode of longitudinal vibrations should be λ/30. To reduce stress concentration in the places of junction between the sections of larger and smaller diameters they are connected with smooth radial junction.

The next step is the choice of diametral size of the waveguide. Given that $d_3 < \lambda/2$.

Further for the creation of the working tool with the large surface of the radiation it is necessary to carry out serial butt-jointing of several half-wave modules (Fig. 2).



a) b)

Fig. 2. The working tool with the large surface of the radiation for 22 and 22.9 kHz

However at the butt-jointing of such half-wave modules into united working tool the increase of operating frequency of the single construction occurs (Fig. 2b).

Fig. 3 shows the dependence of resonance frequency of the working tool on the number of lengths of half-waves obtained by the calculations and modelling with the help of **MFE**.

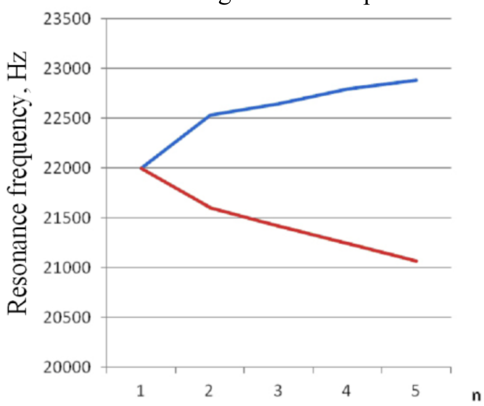


Fig. 3. The dependence of resonance frequency in the working tool on the number of lengths of half-waves (half-wave waveguides)

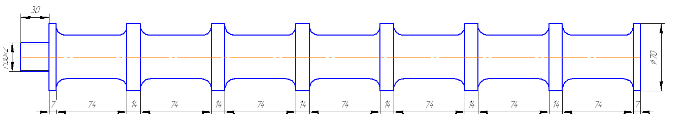
To maintain chosen resonance frequency of the working tool of 22 kHz, it is necessary to reduce the resonance frequency of the initial half-wave element. The dependence of the resonance frequency of the half-wave elemnt on the necessary number of half-waves of the future tool is shown in Figure 3.

Presented dependence is described by the expression:

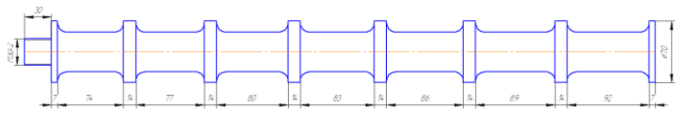
$$f = f_0 n^{-.026}$$

where f_0 is the necessary operating frequency of the working tool with n number of half-waves ($n = 1.2\ldots7$).

Thus specifying necessary quantity of half-wave lengths of the working radiating tool the resonance frequency of one half-wave element can be calculated, further multiunit radiator (Fig. 2a, 4b) will be composed from their butt-jointing at set operating frequency.



a)



b)

Fig. 4. The multiunit radiators for 22.9 and 22 kHz

However both the half-wave module and the whole radiator having variable cross-section along the axis possesses the radial junction between the cylindrical zones. As the radiating surface of the working tool is made with radial roundings, it is possible, that not all radiation areas will be effective. To define the effective area of the radiation of the working tool it is necessary to carry out the researches on the distribution of the vibration amplitude on the surface of the radial junction. The results of modelling and the vibration amplitude of the half-wave radiating element is shown in Fig. 5.

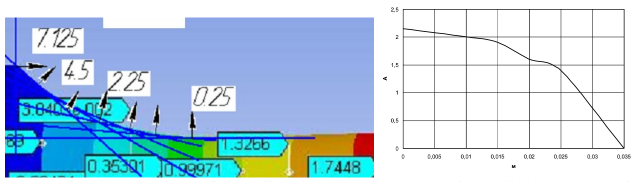


Fig. 5 – The distribution of the vibration amplitude on the radial junction of the radiating element

It is evident from the figure, how the vibration amplitude changes at the distance from its maximum A_{max} (at the cylindrical part of the larger diameter). The value of vibration amplitude corresponding to the value $0{,}5A_{max}$ is chosen as a criterion of the ending of zone of the effective radiation.

The model of the half-wave radiator and the distribution of the vibration amplitude along the axial surface is shown in Fig. 6.

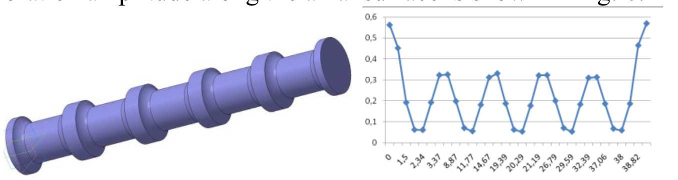


Fig. 6. The model of multiunit radiator consisting of butt-jointed half-wave elements and the distribution of the vibration amplitude along the axis

As it is shown in the figure, the amplitude achieves the upper-range values in the places of the radial junction at the approaching to the cylindrical parts of the larger diameter.

Solving the third of the stated tasks to provide the output of ultrasonic vibrations of high power it is necessary to enlarge the volume of the piezoceramic elements, as they are standard articles and have the maximum size of 50 mm in diameter [3], there is a need to design special transducer.

To increase alternating force it is possible to use 2, 4 and more piezoelements in one packet of the electromechanical transducer.

However such method of power increase of the transducer has limitations, that the piezoelements, which locate inside the packet and do not have the contact with the metal parts of the ultrasonic vibrating system, can be overheated and their ceramics can be depolirized. That is why, the application of the piezoelectric transducers containing of no more than 4 piezoelements is optimum.

To desing the transducer of increased power it was proposed to use the piezoelectric transducer, which allows to sum the power of ultrasonic vibrations generated by the set of piezoelectric element packet of the piezoelectric elements of small size.

Solving of problem of power increase of the piezoelectric transducer by the application of multipacket circuit lets design the vibrating system as a whole.

The construction arrangement using the setting of several piezoelectric transducers on the one radiating cover plate was applied in the paper [1]. The sources of vibrations (the packets of piezoceramics with the reflective cover plate) (5 pieces) were combined with two half-wave radiating cover plate. The plane of joining of ceramics packets was perpendicular to the acoustic axis of the transducer. At this the consumed power of the ultrasonic vibrating system was 2500-3000 VA.

Thus such construction arrangement was chosen as a prototype, that let contunue designing.

The calculations of such transducers are considered in the theory of elasticity. This approach is widely used at the calculations of elastic vibrations in solid-state waveguide transducers and lets calculate precisely the angle between the axis of the piezoelectric packets and the acoustic axis, at which the vibrations on the output radiating end of the transducer will be flat.

However these mathematical calculations are very complicated and require significant time and resort expenditures. It is worthwhile to use **MFE** for the calculations of such transducers.

To develop the piezoelectric transducer of increased power first of all it is necessary to determine the maximum consumed power of the piezoelectric transducer.

A the same time following conditions should be taken into consideration:

1) the input diameter d_1 of the radiating cover plate should satisfy the the condition of location of the number of the piezopackets on its planes, which is enough for obtaining of required consumed power based on the fact, that maximum diameter of the piezoelectric rings produced nowadays is 50 mm;

2) the output diameter of the radiating cover plate should satisfy the condition $d_2 < \frac{\lambda}{2}$.

Taking into account these conditions Table 1 shows developed types of frequency-reduced radiating cover plates of the piezoelectric transducers specifying the consumed power, the number of the piezopackets of input and output diameters.

Table1 – Possible types of the radiating cover plates

P_{nomp}, W	Number of the piezopackets, *N*, pieces	d_1, mm	d_2, mm
3000	3	110	70
4000	4	130	80
7000	7	175	100

However designed transducers with the plane of joining of the vibration sources perpendicular to the acoustic axis of the transducer have the amplification coefficient of the vibration amplitude, which is not enough for solving of stated tasks. Low amplification coefficient minimizes the efficiency included the increase of piezopackets number.

Thus to increase the efficiency of such transducers new type of multiunit transducer with the plane of joining of the vibration sources angularly to the acoustic axis was studied.

For this purpose it is necessary to imagine several one-element half-wave ultrasonic vibrating systems standing angularly to each other, which acoustic axes gather in one point, where planes of output ends of the concentrators cross.

As the transducer is common, it is a body of revolution, which generating line rounds the imaginary concentrators of one-element ultrasonic vibrating systems.

Thus frequency reducing radiating cover plate of the multiunit piezoelectric transducer should be a body of revolution generated by the revolution of the smooth curve around the acoustic axis, which is normal to the plane of the backside with the smaller area of the surface. It is radiating one and from the other side restricted surface, at which there are faces located angularly to this axis at the equal distances from the the center of the radiating surface, which are multiple to the odd number of the fourth length of the longitudinal acoustic wave in the material of the frequency reducing cover plate.

The sources of the vibrations (the packets of the piezoceramic rings consisting of even numbers of the piezoceramic elements) are connected acoustically to the faces.

The acoustic coupling inside the ultrasonic vibrating system is provided due to the fact that the piezoelectric elements are clamped between the frequency reducing radiating cover plate and the reflective frequency reducing cover plate with the force, which many times exceeds the value of the alternating force generated by the piezoelectric elements. The tightening force is provided by the frequency reducing cover plates and pins.

The slope angle of the faces is chosen in order to provide maximum amplification coefficient of the transducer and at the operation of the transducer in consequence of incorrectly chosen angle the flexural vibrations of the sources (the packets of the piezoceramics with the reflective cover plate) do not occur perpendicular to the axis of the pins, by which they are clamped to the frequency reducing cover plate. The appearance of bending vibrations can essentially reduces operating life of the whole construction, as it is known, that piezoceramic materials are significantly brittle [3].

The principal view of the transducers consisting of three, four and seven packets of the piezoceramic elements of 50x20x6 standard size (four elements in the packet) able to satisfy the conditions of 3000, 4000 and 7000 W of consumed power is shown in Fig. 7.

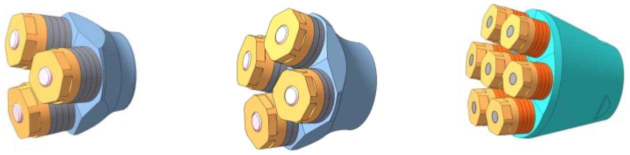


Fig. 7. The principal view of the piezoelectric transducers of increased power

Thus, at the next stage of the designing having input and output diameter of the rediating cover plate the slope angle of the planes is chosen, where the piezoelectric packets will be located.

To determine the optimum slope angle of the plane to the axis of the transducer the researches were carried out included the calculations of the transducers constructions with the different slope angles by the MFE.

The results of modelling for different angle slopes of the plane to the axis of one type of the radiating cover plate are shown in the graphs (Fig. 8, 9)

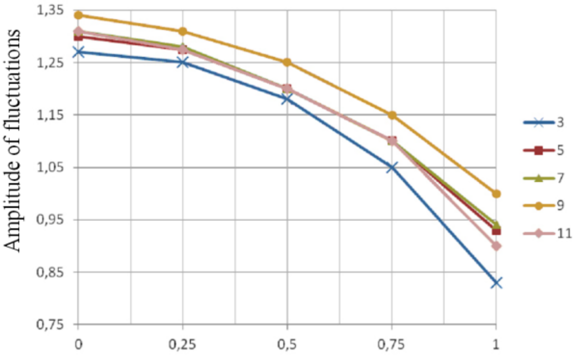


Fig. 8. The distribution of the vibration amplitude on the radiating surface of the cover plate

From Fig. 8 it is evident, that on the radiating surface at the distance from the center to the edge the level of the vibration amplitude reduces, i.e. the nonuniformity on the whole sutface of the radiation occurs. However when the slope angle is 9^0, there is maximum vibration amplitude in the center and the reducing of the amplitude level at the distance from the center.

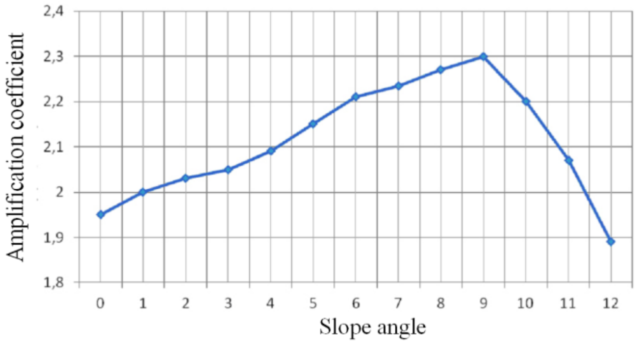


Fig. 9. The dependence of the amplification coefficient of the transducer on the slope angle of the plane

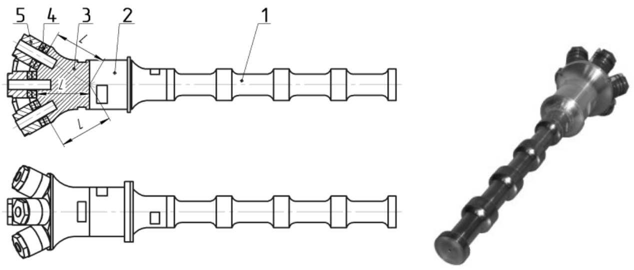
From Fig. 9 it is clear, that as it was mentioned above, when the slope angle is absent, the amplification coefficient is minimal. When the slope angle is 9^0, the maximum amplification coefficient is observed. Further increase of the slope angle leads to the sharp drop of the amplification coefficient of the transducer. It is related to the significant increase of bending vibrations of the piezopackets and the efficiency decrease of the piezotransducer in a whole.

When the slope angle is 9^0, the considerable level of bending vibration amplitude of the piezopacket is observed, though it does not exceed the value, when the distruction of the piezoelements is possible.

It can be concluded, that the angle of 9^0 is optimum at the production of such type of the radiating cover plates.

As a result of carried out investigations the ultrasonic vibrating system was developed, which ready-assembled construction arrangement (the multi-packet piezoelectric transducer with the multi half-wave radiator consisting of series-connected half-wave modules of cross-section in one radiator) is shown in Fig. 10.

The appearance of the developed vibrating system consisting of the piezoelectric transducer allowing to sum the power of the ultrasonic vibrations and the ultrasonic radiator consisting of series-connected half-wave modules of the cross-section is shown in Fig. 10.



1 – the active working tool with the enlarged surface of the radiation, 2 – matching acoustic transformer (the concentrator), 3 – the working frequency reducing cover plate, 4 – the piezoelectric elements, 5 – reflective frequency reducing cover plates

Fig. 10. The construction arrangement and the appearance of the developed ultrasonic vibrating system

The analysis of obtained distribution of the vibration amplitude of the multiunit radiator lets determine, that at the mounting of the developed ultrasonic vibrating system into the running technological volume the following distribution of the ultrasonic vibrations will be provided (Fig. 11), which helps even ultrasonic influence in all volume and the maximum efficiency of the processing of the media flowing through the volume.

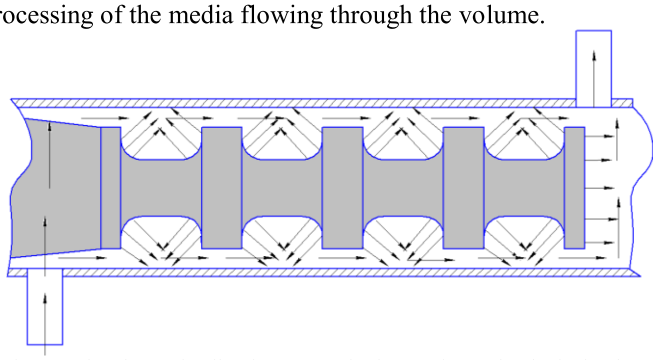


Fig. 11. The ultrasonic vibrating system in the running technological volume

The indirect confirmation of the efficiency and uniformity of the ultrasonic influence during the operation of the ultrasonic radiator in the running volume can be the cavitation wear of the radiating surface.

For further detailed consideration of the cavitation wear of the radiator it is necessary to divide it into the parts from left to right.

Further half-wave elements obtained by the imaginary dissection of the radiator are given in order (Fig. 12).

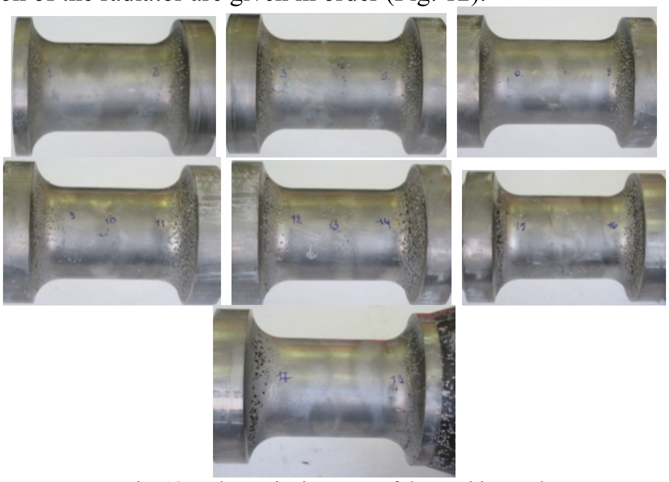


Fig. 12 – The cavitation wear of the working tool

Thus analysing Fig. 12 (determining the degree and the uniformity of the wear) it is evident, that along the radiator in some zones there is typical practically even cavitation wear, which proves the efficiency of the developed and produced ultrasonic vibration system. Moreover according to the value and uniformity of the distribution of the cavitation wear of the radiator after some time of operation in liquid it is possible to evaluate how the results of the modelling of the working tool are correct.

IV. RESULTS OF CARRIED OUT RESEARCHES ARE FOLLOWING

1. Proposed, developed and studied the new approach to solution of the problem of productivity increase of the cavitation ultrasonic processing of liquid media included the design and application of multi half-wave rod-shaped radiators consisting of half-wave modules with the radiating surfaces in the form of smooth junctions between the parts of different diameter.
2. To generate set power of the ultrasonic radiation the piezoelectric transducers providing the summation of mechanical vibrations generated by the single packet piezosystems mounted at the common radiating cover plate of the transducer are proposed and developed.
3. Carried out optimization of the construction arrangement of multi half-wave multipacket vibrating system lets create the radiators with the specified characteristics of power and intensity of radiation.

REFERENCES

[1] http://www.hielscher.com/ultrasonics/i4000_p.htm
[2] IAMP – 2010: Materials 7th All-Russia scientifically-practical conference / Alt. Teh. Un y, BTI. – Biysk: Publishing house Alt.gos. teh. Un y, 2010.244 with.
[3] IAMP – 2010 / Alt.Stait. The. Univ., BTI – Biysk., 2010.
[4] Zhukov S.N.piezoelectric ceramics: principles and application. – Minsk: Open Company "FU Auniform", 2003. – 112 with.
[5] Rosenberg L.D.physical of a basis of ultrasonic technology. – M: the Science, 1970. – 688 with.
[6] Teumin, I.I.ultrasonic to-lebatelnye systems [Text] / I.I.th. – M:, 1959. – 331 with.

Vladimir N. Khmelev (SM'04)— pro-rector at Biysk technological institute, professor, Full Doctor of Science (ultrasound). Honored inventor of Russia. Laureate of Russian Government premium for achievements in science and engineering. Area of scientific interests is application of ultrasound for an intensification of technological processes. IEEE member since 2000, IEEE Senior Member since 2004. His biography published in 7th issue of book "Who is who in scientific and engineering"

Sergey V. Levin was born in Bisyk, Russia 1981. He is engineer of Biysk Technological Institute.

Sergey N. Tsyganok was born in Biysk, Russia, 1975. Now he is Ph.D (Machinery), he received degree on information measuring engineering and technologies from Altay State Technical University, key specialist of electronics. Laureate of Russian Government premium for achievements in science and engineering. His main research interest are development of high -effective multifunctional oscillators for ultrasonic technological devices.

Sergey S. Khmelev was born in Prokopievsk, Russia, 1985. Now hi is student of Biysk Technological Institute. His research interests is design and construction ultrasonic oscillation system.