# Design of process equipment exposure sources for ultrasonic absorption of greenhouse gases

*V.N.* Khmelev[1*], *R.N.* Golykh[1], *S.N.* Tsyganok[1], and *A.R.* Barsukov[1]

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

**Abstract.** The work aims at improving the efficiency of greenhouse gas utilisation processes, namely carbon dioxide. The principle of operation of the designed equipment is to realise the process of ultrasonic absorption (absorption of gas by liquid) when carbon dioxide is fed over the surface of the liquid, in which cavitation occurs. The source of the cavitation action is a plate that oscillates with a given frequency and amplitude. The efficiency of the ultrasonic gas absorption process is determined by the parameters of plate oscillations. In particular, to ensure the necessary and sufficient amplitude of plate oscillations and uniformity of its distribution along the plate, it is proposed to solve the problem of optimal placement of the required number of ultrasonic emitters of a given size. As a criterion of optimality, it is proposed to use the integral power of oscillations of the whole plate, formed by a certain number of emitters. The proposed and developed numerical model of oscillation formation in the plate is based on the solution of the biharmonic equation for the distribution of amplitudes of oscillations, taking into account the finiteness of its thickness and provides the choice of the number, location, and size of ultrasonic emitters required to solve a particular problem. The simulation results allowed us to establish that the optimal location of the emitters depends on specific characteristics that must be taken into account when solving the problem of optimising the size and location of ultrasonic emitters for each particular plate. The calculations showed high efficiency of the created model and the possibility of its practical application for solving the problems of utilisation of greenhouse gas emissions in agriculture.

## 1 Introduction

Ultrasonic (US) influence [1-4] is becoming more and more widespread for intensification of technological processes. In the course of numerous scientific studies, as well as on examples of successful commercial implementation of ultrasonic equipment [5, 6], the high efficiency of high intensity ultrasound has been repeatedly confirmed in the initiation of the flow and intensification of technological processes in substances in various aggregate states [7-16].

In practice, when implementing technological processes, the most widespread are the systems based on the use of a single ultrasonic vibrating system (USCS) (i.e., systems with

* Corresponding author: vnh@ bti.secna.ru

single or multi-package piezoelectric transducer, rod or disc emitters), having limited in size radiating surface of the working tools. In this case, the oscillating system is powered by an appropriate generator of calibrated ultrasonic oscillations [17].

Obviously, this approach to the realisation of ultrasonic vibrations impact on the processed media or objects has a limited area of impact or does not provide uniformity of the vibration amplitude distribution in the volumes of liquid media.

This approach is not applicable in realisation of processes in thin layers of various materials created on flat surfaces of various sizes. The necessity of realising such processes arises, for example, at intensification of absorption of gases by liquids when solving the problem of film absorption of carbon trace from the atmosphere or undesirable impurities from technological and medical gases. In addition, similar problems need to be solved in the dispersion of liquids, heat removal from heated radiators, drying of formed coatings, removal of ice and foreign coatings [18-19]. In particular, when solving the problems of de-icing or drying of solid sheet materials, it is necessary to realise the impact with the highest possible power and also with the largest possible area. Thus, all these tasks can be solved only by forming oscillations at ultrasonic frequency with a given amplitude on a surface of larger area. It is obvious that the effective realisation of processes in a liquid film or coating can be provided only at transfer of all area of interfacial surface of the necessary and sufficient power of ultrasonic oscillations.

Given the above, there is a need to develop a fundamentally new design consisting of an array of ultrasonic radiators capable of providing uniformity of oscillation of the surface of a flat physical object (plate) with a given amplitude.

Since it is practically impossible to solve this multifactorial problem by means of experimental studies, theoretical studies aimed at revealing the features and regularities of joint operation of ultrasonic radiators in the formation of oscillations on a certain object are needed.Thus, a simulation of the vibrational process of a flat physical object of finite thickness is necessary, carried out by an array of sources of ultrasonic action for the subsequent optimisation of the location and size of the emitters on the surface to increase the uniformity of the distribution of amplitudes of oscillations in its areas, oscillating during the implementation of the technological process. Ensuring the uniformity of process implementation due to the optimisation of vibration distribution will provide an increase in the efficiency of intensification of the implemented technological process, with minimisation of the primary financial costs for the purchase of ultrasonic equipment and energy costs to ensure its performance.

## 2 Materials and methods of problem solving, assumptions made

It was decided to use the Morley finite element method to calculate the acoustic field. The linear theory of elasticity serves as the foundation of the conducted research. To search for the optimums of distribution uniformity, a software implementation of the optimisation brute-force procedure generating program modules for the FreeFEM++ compiler is required.

## 3 Results

To solve the problem of finding the distribution of US oscillations on the flat surface of a plate of finite thickness, with boundary conditions on the radiators, it is necessary to define the mathematical formulation. The computational domain has the following form, which is shown in Fig. 1.

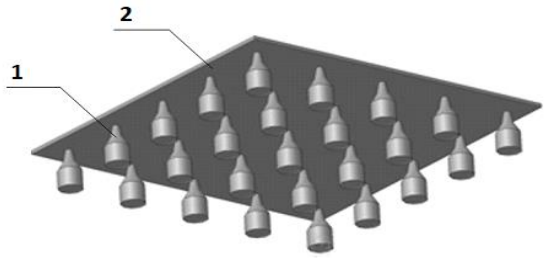


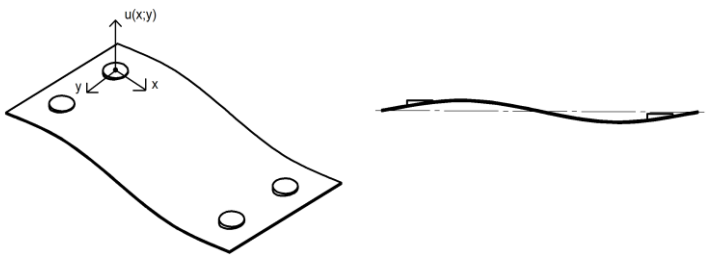

**Fig. 1.**A plate of finite thickness with ultrasonic emitters attached to it (1 - ultrasonic emitter; 2 - plate)

To calculate the distribution of vibration amplitudes over the surface of the body, the biharmonic equation (1) is used, which follows from the equations of the linear theory of elasticity.

$$\nabla^4 u - k^4 u = 0, \tag{1}$$

where u is the complex amplitude of vertical displacements of the plate, m; k is the wave number of the plate, $m^{-1}$.

The axonometric projection and side view of a bending and oscillating plate with a placed array of radiators are shown in Figure 2.




a b

**Fig. 2.** Projection of a bending and oscillating plate with a placed array of ultrasonic emitters (a - axonometric projection; b - side view)

The wave number for a finite-thickness plate, in turn, depends on its stiffness (2).

$$D = \frac{Eh^3}{12\left(1-\nu^2\right)}, \tag{2}$$

hereEdefines modulus of elasticity of the plate material, Pa; h - plate thickness, m; ν - Poisson's ratio of the plate.

Depending on the stiffness coefficient of the plate, the wave number is determined according to the expression (3).

$$k = \sqrt[4]{\frac{\rho h \omega^2}{D}} = \sqrt[4]{\frac{12\left(1-\nu^2\right)\rho h \omega^2}{Eh^2}}, \tag{3}$$

where ρ is the density of the plate material, kg/m$^3$; ω is the circular frequency of ultrasonic vibrations, s$^{-1}$.

To determine the speed of sound in a plate of finite thickness, it is necessary to use the corresponding equation for determining the speed of sound propagation in this plate: $c = \frac{\omega}{k}$.

The vibration equation is supplemented by boundary conditions. At the plate boundary, the condition of absolutely rigid fixation of the boundaries is fulfilled (4).

$$u = 0, \quad \frac{\partial u}{\partial n} = 0 \tag{4}$$

Hereinafter, n is the normal vector, which lies in the plane of the plate and is directed perpendicular to the line bounding the plate or the area of the ultrasonic transmitter mounting.

On the boundary of the area of the transmitter attachment to the plate the condition is fulfilled (5).

$$u = A, \quad \frac{\partial u}{\partial n} = 0, \tag{5}$$

where A is the amplitude of the transmitter oscillations, m.

In turn, the amplitude of vertical displacements of the plate over the entire area of the transmitter mounting is equal to A.

The plate with radiators placed on its surface is schematically represented in the Figure 3.

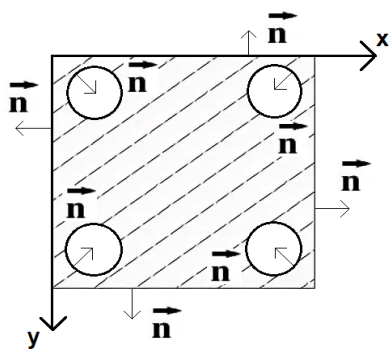



**Fig. 3.** Schematic representation of a plate with ultrasonic emitters (top view)

The Morley finite element method is used to calculate the amplitude distribution of vertical displacements. The essence of the method is based on the representation of the biharmonic equation (1) in the form of a boundary integral equation (6).

$$\int_S \left( \frac{\partial^2 u}{\partial x^2} \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \frac{\partial^2 v}{\partial y^2} + 2 \frac{\partial^2 u}{\partial x \partial y} \frac{\partial^2 v}{\partial x \partial y} \right) dS - \\ - \int_S k^4 uv dS = 0, \tag{6}$$

where v is the trial function.

The Morley finite element method was implemented as a software module for the FreeFEM++ compiler. The created software module allows us to calculate the amplitude distribution of vertical displacements of the plate at given diameters of the attachment regions, sizes, locations, amplitudes of oscillations and number of ultrasonic emitters. The created software module provides an order of magnitude higher performance of calculations in comparison with the classical three-dimensional finite element method (reduction of calculation time up to 10 times at similar sizes of elements of the calculation grid on the plate surface). The software module was further taken as a basis for solving the problem of optimisation of the vibration amplitude distribution.

To set the optimisation problem, we initially analysed the dependences of the efficiency of the process occurring at the liquid-gas film interface on the example of gas absorption on the amplitude of ultrasonic oscillations.

In the publication [20], previously presented by the authors of this article, the dependences of the specific surface of the interfacial boundary on such liquid properties as: viscosity (Figure 4) and surface tension (Figure 5) are given.

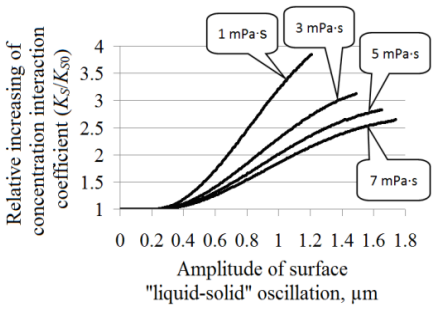



**Fig. 4.**Dependences of the specific surface of the interfacial boundary on liquid viscosity

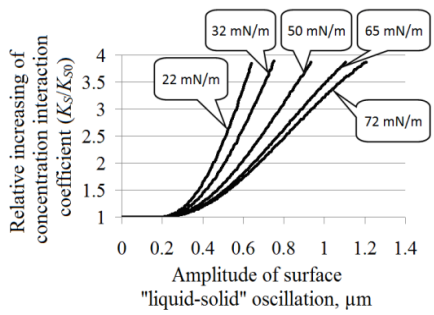



**Fig. 5.**Dependences of the specific surface of the interfacial boundary on the surface liquid tension

The results obtained suggest that the absorption rate depends directly on the amplitude of oscillations and is proportional to it.

The final efficiency of the processes in this case is determined by the input energy, which in turn is almost all transferred to the liquid film, since the plate thickness is small compared to its length and width. In addition, along with energy consumption, to ensure simplicity, higher reliability, reduced cost of construction and maintenance of the design of the ultrasound apparatus under consideration, it is necessary to ensure that one transmitter provides the introduction of as much power as possible (to use as few transmitters as possible per unit of input energy).

It was therefore decided to optimise the power delivered per transmitter.

The optimisation problem is to find the distribution of the acoustic field on the surface that maximises this parameter. In this case, the optimality criterion is the power allocated on the surface (7).

$$P = \rho c \omega^2 \frac{\int u^2 \, dS + A^2 \cdot N_{em} \cdot S_{em}}{2N_{em}}, \tag{7}$$

whereuis the amplitude of oscillations at the surface boundary, m; $\rho c$ – wave impedance of the sounding medium; A defines amplitude of oscillations at the radiators, m; $S_{em}$issurface area of the end face (mounting area) of one transmitter, $m^2$; $N_{em}$isnumber of emitters.

The optimal field distribution is obtained by solving the biharmonic equation with boundary conditions on the radiators and Dirichlet boundary conditions on the boundary of the region. The optimality criterion is calculated from the found field distribution.

To achieve a uniform distribution of the plate vibration amplitudes, an optimisation procedure based on the brute force method must be applied (a program is developed that implements the optimisation and calls the software module to calculate the distribution of vertical displacements of the radiating surface). In the process of optimisation, it is required to investigate different variants of the location of the emitters relative to the plate, as well as the influence of their size on the change of the optimisation criterion.

Further, the numerical analysis of the developed model is carried out. The numerical analysis was carried out on the example of a plate with radiators having the same diameter located on the plate surface at a uniform distance from each other in the form of a matrix. At each iteration of the configuration calculation, the number of emitters in the X and Y axes is set. For each transmitter arrangement configuration, including configurations from 2x2 to 10x10, the power per transmitter is calculated.

The plate size was 200 mm x 200 mm and the face diameter of an individual transmitter (diameter of the mounting area) was 10 mm.

The obtained results are presented in Table 1.

**Table 1.** Powervalues $\frac{P}{\rho c \omega^2}$ [$m^2$] per individual transmitter for different numbers of transmitters

| **Y** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **2** | 0.008 | **0.019** | 0.018 | 0.014 | 0.011 | 0.009 | 0.007 | 0.007 | 0.006 | |
| **3** | **0.019** | 0.017 | 0.015 | 0.012 | 0.010 | 0.008 | 0.007 | 0.006 | 0.006 | |
| **4** | 0.018 | 0.015 | 0.012 | 0.009 | 0.008 | 0.007 | 0.006 | 0.005 | 0.004 | |
| **5** | 0.014 | 0.012 | 0.009 | 0.008 | 0.006 | 0.005 | 0.005 | 0.004 | 0.004 | |
| **6** | 0.011 | 0.010 | 0.008 | 0.006 | 0.005 | 0.004 | 0.004 | 0.003 | 0.003 | |
| **7** | 0.009 | 0.008 | 0.007 | 0.005 | 0.004 | 0.004 | 0.003 | 0.003 | 0.003 | |
| **8** | 0.007 | 0.007 | 0.006 | 0.005 | 0.004 | 0.003 | 0.003 | 0.002 | 0.002 | |
| **9** | 0.007 | 0.006 | 0.005 | 0.004 | 0.003 | 0.003 | 0.002 | 0.002 | 0.002 | |
| **10** | 0.006 | 0.006 | 0.004 | 0.004 | 0.003 | 0.003 | 0.002 | 0.002 | 0.002 | |
| | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **X** |

Analysing the data presented in Table 1, we can conclude that the highest value of power per transmitter is achieved when using a 2x3 (3x2) configuration of the ultrasound transmitter arrangement (Figure 6).

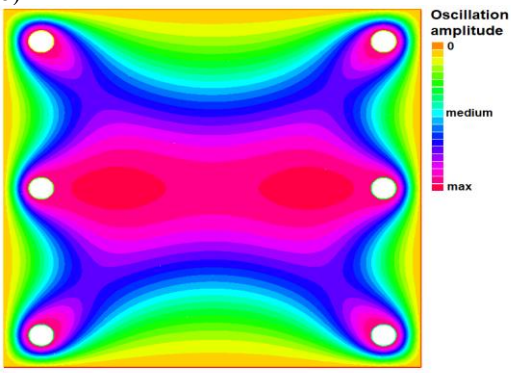


**Fig. 6.** Visual distribution of oscillation amplitudes at the optimum configuration of transmitter locations

Thus, the results of modelling show that the most effective field radiation through a flat surface is achieved at the established configuration of ultrasonic emitters arrangement. This confirms the possibility of using a certain number of emitters for the effective implementation of technological processes that require the creation of vibrations of a certain amplitude on large surface areas.

Data on the nature of power dependence on combinations of the number of radiators were analysed using visual methods, as presented in Figure 7.

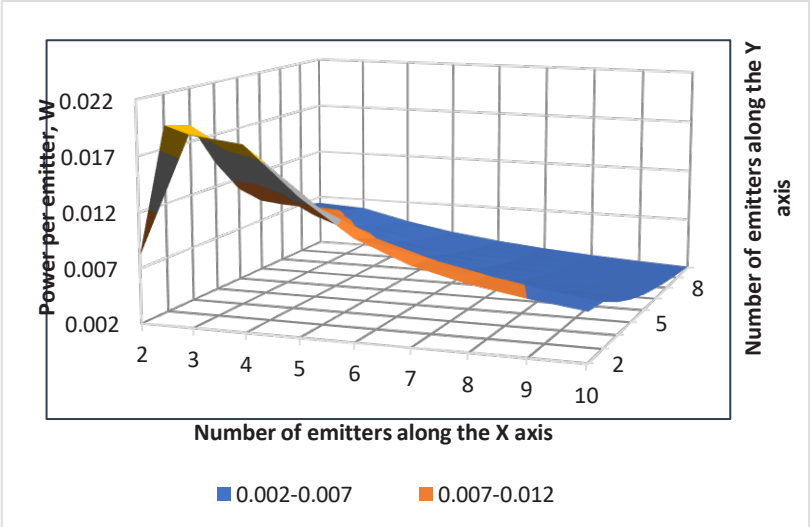



**Fig. 7.** Dependence of the power attributable to the transmitter $\frac{P}{\rho c \omega^2}$ [m$^2$], from combinations of emitter locations on a flat surface

Figure 7 shows that when increasing the number of radiators from 1x1 to 2x2, 2x3, 3x2, a sharp rise in power begins, but then, with further increase in the number of radiators along the X and Y axes, a drop in power is observed, indicating the inexpediency of further increase in the number of radiators.

Thus, based on the analysis of the obtained data, we can conclude that the use of a certain number of radiators, arranged in a certain matrix configuration, provides efficiency and uniformity of acoustic field distribution. Only in this way the successful implementation of technological processes requiring the creation of ultrasonic vibrations on huge interfacial surfaces, the size of which many times exceeds the thickness of the layer of the sounded medium, is ensured.

Further investigations were aimed at revealing the influence of the diameter of a single transmitter on the efficiency of oscillations introduction into the liquid film. Calculations were carried out for the most common radiators having diameters of transmitter mounting equal to 5 mm, 10 mm, 15 mm and 20 mm.

Based on the calculations, it was found that an increase in the diameter of the transmitter mounting surface leads to an increase in the power per transmitter, indicating that it is important to consider the effect of this size to ensure the optimum configuration of the

transmitter arrangement. A larger connection size allows for more uniform plate oscillation, as evidenced by the power vs. transmitter size relationship shown in Figure 8.

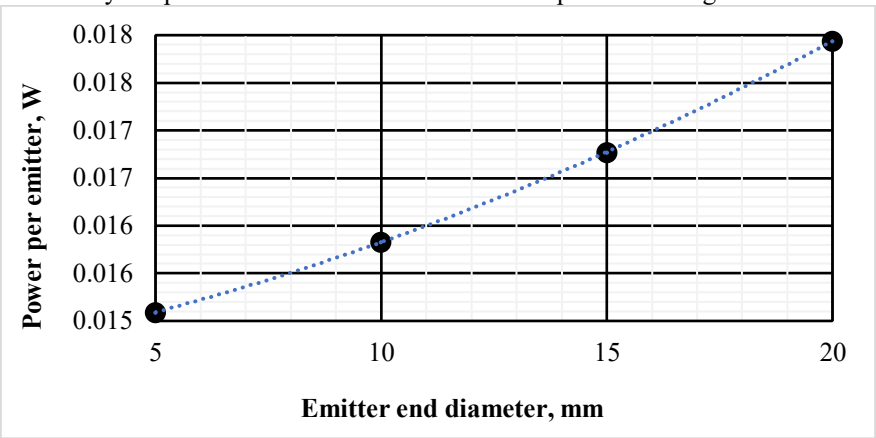



**Fig. 8.** Dependence of the power delivered to the transmitter on the diameter of the transmitter face

The visual distribution of oscillation amplitudes over a flat surface at different sizes of emitters is presented in Figure 9.

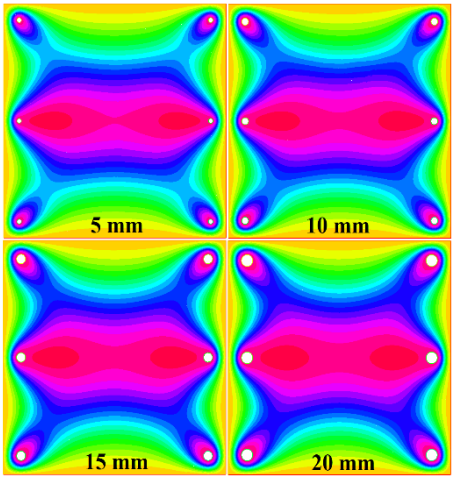



**Fig. 9.** Visual distribution of oscillation amplitudes on a flat surface for different transmitter sizes

It is necessary to choose the optimal number of emitters, because further increase of the connection size will not provide the required amplitudes for the process realisation or will require the use of multi-package piezoelectric transducers.

## 4 Discussion

A numerical model is proposed and developed, which allows to optimise the number and location of emitters to ensure maximum energy efficiency of ultrasonic oscillations of flat physical objects (plates) in contact with the medium of technological process implementation, which is a thin layer covering the entire surface of the object (e.g., a film of liquid, which provides absorption of gas; a layer of ice, which must be separated; a layer of capillary-porous substance containing moisture, which must be removed; a layer of capillary-porous substance containing moisture, which must be removed; a layer of capillary-porous

substance containing moisture, which must be removed; and a layer of capillary-porous substance containing moisture. The model is based on the optimality criterion, for which the maximum of the integral radiation power attributed to the number of emitters is taken. On the basis of the analysis of literature data on the influence of energy efficiency of exposure on the rate of processes that require the formation of ultrasonic vibrations of large interfacial surfaces (absorption, drying, de-icing) the expediency of the proposed criterion is proved.

## 5 Conclusions

The model made it possible to reveal the influence of the number and size of radiators on the efficiency of transmitting oscillations to a physical object.
The existence of an optimal number of radiators has been established, in which the efficiency of energy transfer is maximised.

The growth of energy transfer efficiency with the increase of the transmitter diameter has been revealed, which, however, is limited under the condition of formation of uniformly distributed oscillations at the end using a single-package piezoelectric transducer.
The created numerical model can serve as a basis for the design of ultrasonic equipment, making an effective impact on flat physical objects of finite thickness.

## 6 Acknowledgements

The research was supported by the RNF grant 22-29-00828 "Cavitation-acoustic formation of multi-connected gas-liquid interfacial surface for solving the problem of highly efficient gas absorption".

## References

1. E.V. Boev, V.G. Afanasenko, N.I. Boeva, J. Phys.: Conf. Ser. **1515(4)**, (2020) https://doi.org/10.1088/1742-6596/1515/4/042001
2. V. Shtepa, M. Balintova, A. Shykunets, et al., Fermentation **9(3)**, (2023) https://doi.org/10.3390/fermentation9030225
3. V.N. Khmelev, R.V. Barsukov, S.N. Tsyganok, et al., Fibre Chemistry **53(9)**, 1–4 (2022) https://doi.org/10.1007/s10692-022-10310-9
4. S. Ojha, J. Mallia, D. Spiteri, et al., Emerging Food Processing Technologies 113–131 (2022) https://doi.org/10.1007/978-1-0716-2136-3_8
5. V.N. Khmelev, R.V. Barsukov, A.R. Barsukov, et al., South Siberian Scientific Bulletin **4(44)**, 106-109 (2022) https://doi.org/10.25699/SSSB.2022.44.4.003
6. L. Svilainis, Applied Sciences 2(16), (2022) https://doi.org/10.3390/app12168284
7. B. Naveena, P. Armshaw, J. Pembroke, Biotechnology for Biofuels **8(140)**, (2015) https://doi.org/10.1186/s13068-015-0321-0
8. L. Yang, X. Li, W. Li, et al., Sep. Purif. Technol **227**, (2019) https://doi.org/10.1016/j.seppur.2019.115701
9. S.V. Meshcheryakov, A.M. Gonopolsky, M.S. Mullakayev, et al. Ecology and Industry of Russia **22(2)**, 8–12 (2018) https://doi.org/10.18412/1816-0395-2018-2-8-12
10. N.V. Thombre, A.P. Gadhekar, A.V. Patwardhan, et al., Ultrason. Sonochem. 62, (2019) https://doi.org/10.1016/j.ultsonch.2019.104891

11. V. Melnyk, V. Kosova, Z. Ostapenko, et al., Vibrations in Engineering and Technology, (2022) https://doi.org/10.37128/2306-8744-2022-1-5
12. D. Huang, K. Men, D. Li, et al., Ultrason. Sonochem. 63, (2020) https://doi.org/10.1016/j.ultsonch.2019.104950
13. F. Ishtiaq, R. Farooq, U. Farooq, et al., World Applied Sciences Journal **6(7)**, 886–893 (2009)
14. E. Nascimento, A. Mulet, J.L. Ascheri, J. Food Eng. **170**, 108–118 (2016) https://doi.org/10.1016/j.jfoodeng.2015.09.015
15. H.D. Mobarakeh, M. Miner, L. Wang, et al., Drying Technol. **40(11)**, (2021) https://doi.org/10.1080/07373937.2021.1929296
16. J.V. Garcia-Perez, J.A. Carcel, E. Riera, et al., Drying Technol. 30(11), 1199–1208 (2012) https://doi.org/10.1080/07373937.2012.675533
17. V.N. Khmelev, Y.M. Kuzovnikov, M.V. Khmelev, South Siberian Scientific Herald **1(17)**, 5-13 (2017)
18. X. Liang, G. He, J. Wang, et al. Appl. Therm. Eng. **200(4)**, (2021) https://doi.org/10.1016/j.applthermaleng.2021.117719
19. L. Maio, J. Moll, V. Memmolo, et al., Mech. Syst. and Signal Process. **173(1)**, (2022) https://doi.org/10.1016/j.ymssp.2022.109025
20. V.N. Khmelev, R.N. Golykh, S.N. Tsyganok, et al., WSEAS Trans. on Fluid Mech., **16**, 168–179 (2021) https://doi.org/10.37394/232013.2021.16.16