УДК 621.647.23
DOI: http://dx.doi.org/10.20535/2521-1943.2018.82.127128

Investigation of the processes of the acoustic apparatus with the processing technological environment power interaction

Iryna Bernyk

Vinnytsia National Agrarian University, Vinnitsa, Ukraine

Received: 27 February 2018/ Accepted: 12 March 2018

***Abstract**. The physical picture of the processes of the apparatus with the processing technological environment interaction is determined, the change in its rheological properties were taken into account. The effectiveness of cavitation effects from the initial to the final processing stage is caused by the contact pressure and the speed of its propagation. A lot of power characteristics and parameters were considered for the effective implementation of the cavitation process. On the basis of these parameters, the energy of the process is accumulated by expanding the bubble from the initial balanced to its maximum radius. The basis of accumulation is the tensile forces in the phase of desiccation of the acoustic wave. The graphs of the contact pressure dependence on the key parameters of the process and the determination of the regularity of its change are made. The modes and parameters for leakage of energy-efficient acoustic process of different environments processing were proposed. The directions of of research results application and their further development were determined.*

Keywords: *acoustic apparatus, cavitation process, interaction, energy, environment, rheological properties, parameters, pressure.*

Introduction. The technological processes implementation is carried out by energy transforming of the acoustic apparatus sound field into a technological environment. The energy of the acoustic apparatus is spent on the formation of shock waves, thermal energy, local electrification of bubbles, and excitation of the sonoluminescence and formation of free radicals. At the same time there is a significant change in the rheological properties of the technological environment. The characteristic stages of such process are the stages of origin, development and closure of bubbles in a certain volume of the technological environment. The constantly changing conditions and state of environment under loading causes the formation of complex mass and heat transfer. As a result, the mathematical description of such process is a very difficult task. That is why most works researched the dynamics of one cavitation bubble and the corresponding correlation of the results on the motion of the entire cavitation area. Certainly, this approach expanded the understanding of cavitation process basic nature but it does not solve the problem of the interaction of the cavitation apparatus and the technological environment. The initial energy concentrates in the contact area; it is further transferred to the technological environment and influences the effectiveness of the cavitation process. Therefore, the task of researching the interaction of the cavitation apparatus and the technological environment on the basis of determination and transformation of pressure on the environment as the dominant energy parameter is rather actual.

Literature Review and Problem Statement. The energy transmitted from the acoustic apparatus to the environment is determined by the modes (harmonic or pulsed) and its parameters (contact pressure and speed) [1, 2]. The physical effects arising from these modes and parameters in a liquid or other technological environment are characterized by the stages of origin, development and closure of bubbles in the created cavitation area of this environment [3–5]. Various technological processes for improving existing characteristics or creating new materials are carried out [6–8]. So, we have the system acoustic apparatus – the technological environment; its joint interaction depends on the implementation of energy-efficient acoustic processing of environment [9, 10]. Historically, most works were devoted to a separate research of the behavior of technological environments or acoustic emitters. As research results, the process of formation and development of the cavitation area with technological environments processing parameters were described [11–13]. Different designs of acoustic devices are proposed [15, 16]. Paying tribute to these works that have revealed and extended the idea of the theory and practical solutions we should mention that today there are virtually no models and solutions that fully describe the process of interaction between the ultrasound apparatus and the treated environment. There is no research of changing treated environment rheological and acoustic properties effect on the qualitative and

✉ Iryna Bernyk
iryna_bernyk@i.ua

quantitative characteristics of the contact pressure. An important component of the rheological properties of the treated environment is the viscosity because it significantly influences the formation of bubbles and their movement [17, 18]. At the same time, there is no physical model that takes into account the viscous properties of the environment.

Aim and tasks of the research. The research purpose is to determine the process qualitative and quantitative characteristics of power interaction of acoustic apparatus and treated environment.

The tasks are the following.

1. Justification and calculation of the main characteristics of the model of power interaction of the ultrasound apparatus and the processing environment.
2. Investigation of the ultrasonic apparatus acoustic parameters influence on the rheological properties of the environment on the contact pressure.
3. Propose the purposeful use of certain parameters of the power interaction of the ultrasound apparatus and the processing medium.

Methodology and methods of pressure research in the contact zone of the system acoustic apparatus - technological environment

The interaction of the ultrasound apparatus with the environment is complex. Therefore, an important aspect for research conducting is the adoption of such physical and mathematical model prerequisites that most adequately reflects the actual process of interaction of the ultrasound apparatus and the environment. An important condition for the model correct choice is the exact reconstruction of the qualitative force transformation of the ultrasound apparatus into the processing environment. In accordance with the above prerequisites the following assumptions were made for constructing a mathematical model for determining the contact pressure with taking into account the interaction of the acoustic apparatus and the technological environment. The surface of the acoustic apparatus in the contact zone with the processing environment carries intrusive harmonic oscillations; it is modeled by discrete parameters. The technology environment is modeled by a system with distributed parameters considering elastic and viscous properties. The general system of acoustic apparatus – the technological environment is considered as a common, subjugated to a single viobacoustic process in the motion equations for the determination of contact pressure. The equations are solved by the Fourier method. The first methodological research approach is to assess the influence of apparatus acoustic parameters on the working process of the origin, development and closure of the cavitation area bubbles stages. It is caused by the possible influence of the contact pressure on the cavitation process. The second methodological research approach is to determine the effect of changing the density, the elasticity, viscosity of the process environment and the velocity of propagation of waves in environment. The research results processing are based on generally accepted methods of mathematical statistics, a systematic approach to the analysis and synthesis of decision-making.

Investigation of the influence of the ultrasound apparatus acoustic parameters and the environment rheological properties on the contact pressure

The key parameter of the gas and air bubbles evolution in the acoustic field is the sound pressure that forms in the contact zone of the system acoustic apparatus and environment. Because of the acoustic apparatus force on the liquid or other technological environment, the creation of bubbles and their development is due to the presence and appropriate influence of the following characteristic pressures: $P_{кв}$ – pressure of the acoustic apparatus in the zone of contact with the environment (sound pressure); $P_{ст}$ – hydrostatic pressure; $P_{р}$ – pressure in the liquid; $P_{п}$ – surface forces tension; $P_{в}$ – viscous frictional force; $P_{б}$ – internal pressure in the cavitation bubble; $P_{г}$ – gas pressure; $P_{нп}$ – pressure of saturated vapor in a liquid. The pressure of the acoustic apparatus in the zone of contact with the environment (sound pressure) and hydrostatic pressure represent the action of external forces. Other types of pressure are internal reactive actions; they represent the corresponding stresses in the fluid medium and in the cavitation area bubbles that arise as a result of external actions. To break the ideal fluid (carrier phase) it is necessary to overcome the forces of intermolecular interaction; they are $3 \cdot 10^9$ ... $3 \cdot 10^{10}$ Pa [19]. If the amplitude of sound pressure is up to 10^5 Pa for water or $3 \cdot 10^5$ ... $5 \cdot 10^5$Pa for oil [19], the vibration amplitudes of the bubbles radius equals with the initial radius, that’s why their harmonic oscillations are violated. This local pressure increase is accompanied by a shock wave with small amplitude of pressure. The shock wave pressure does not exceed $2 \cdot 10^5$ ... $3 \cdot 10^5$ Pa at distances of about 5 μm. A further increase of the sound pressure amplitude leads to a significant increase in the shock waves pressure amplitude occurs in the case of cavitation bubbles collapse. If collapse is inside the bubble great pressures are created up to 10^9 Pa. When the sound pressure amplitude increases above a certain critical value the cavitation bubbles reach critical sizes at which their degeneration occurs in the long-lived [19]. Such bubbles for a large number of periods make oscillations near their maximum sizes (more than 100-1000 μm) [10]. Long-lived bubbles are practically not collapsed and, consequently, do not have any intensifying effect on the flow of technological processes in liquid media. Since the size of the bubble changes slightly the energy consumption on bubble size changing is small. To evaluate the effect of the above mentioned types of pressure we are considering the pulsations equation of the cavitation bubble [20]:

$$R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2+\frac{1}{\rho_{ð}}\left[P_0-P_{ï}-P\sin(\omega t)+\frac{2\sigma}{R}-\left(P_0+\frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma}\right]=0 \qquad (1)$$

Taking into account the viscosity in equation (1) makes it possible to obtain the complete equation of the pulsations of a cavitation bubble:

$$R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2+\frac{1}{\rho}\left[P_0-P_{ï}-P\sin(\omega t)+\frac{2\sigma}{R}+\frac{4\eta}{R}\frac{dR}{dt}-\left(P_0+\frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma}\right]=0 \qquad (2)$$

The solution of this differential equation that is the dependence of the relative radius of the bubble R/R_0 on the dimensionless time ωt [21], confirms the distribution of the sound pressure amplitudes.

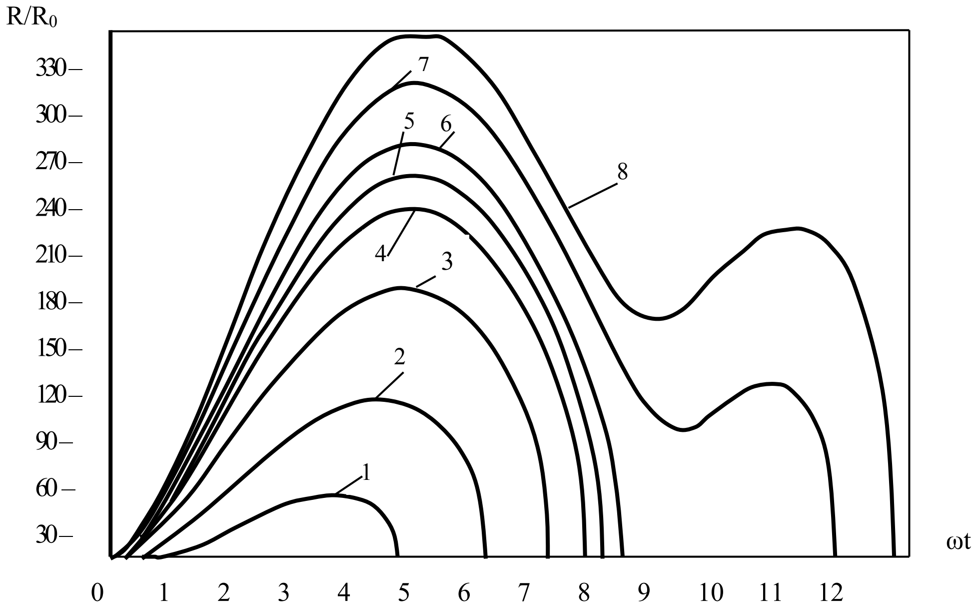


Fig. 1. The dependences of the relative radius of the bubble R/R_0 on the dimensionless time ωt for different sound pressure amplitudes

The curves are obtained for the initial equilibrium radii of the bubbles $R_0 = 10^{-6}$ m; they are pulsating adiabatically in water at a temperature 20°C at atmospheric pressure $P_0 = 10^5$ Pa. Acoustic oscillation frequency is 22 kHz.

The increase in the cavitation bubble maximum radius is directly proportional to the amplitude of the sound pressure as it follows from the graphs. So, the value of the maximal radius of the cavitational bubble is an important parameter for estimating the cavitational area. Change in contact pressure $P_{кв}$ and transformation of the cavitation bubble size $R_{min\text{-}max}$ for one period of oscillations (fig. 2) shows a direct dependence between the change in pressure and

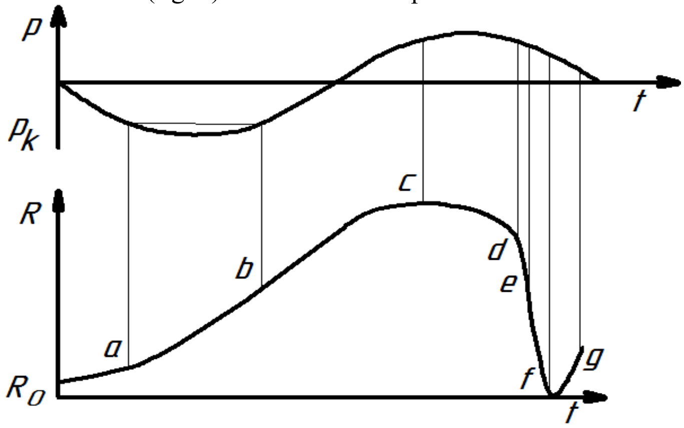


Fig. 2. Change in contact pressure $P_{кв}$ and transformation of the cavitation bubble size $R_{min\text{-}max}$ for one period of oscillations

the size of the cavitation bubble. A similar schedule is presented in [22]. However, in our case, some specifications have been made in the figure; they consist in the fact that due to energy loss there is a phase shift between the active force and the displacement of the bubble in the real process.

Fig. 3 shows a program for calculating the wave coefficients and contact pressure for the analytical dependencies obtained in the work [23].

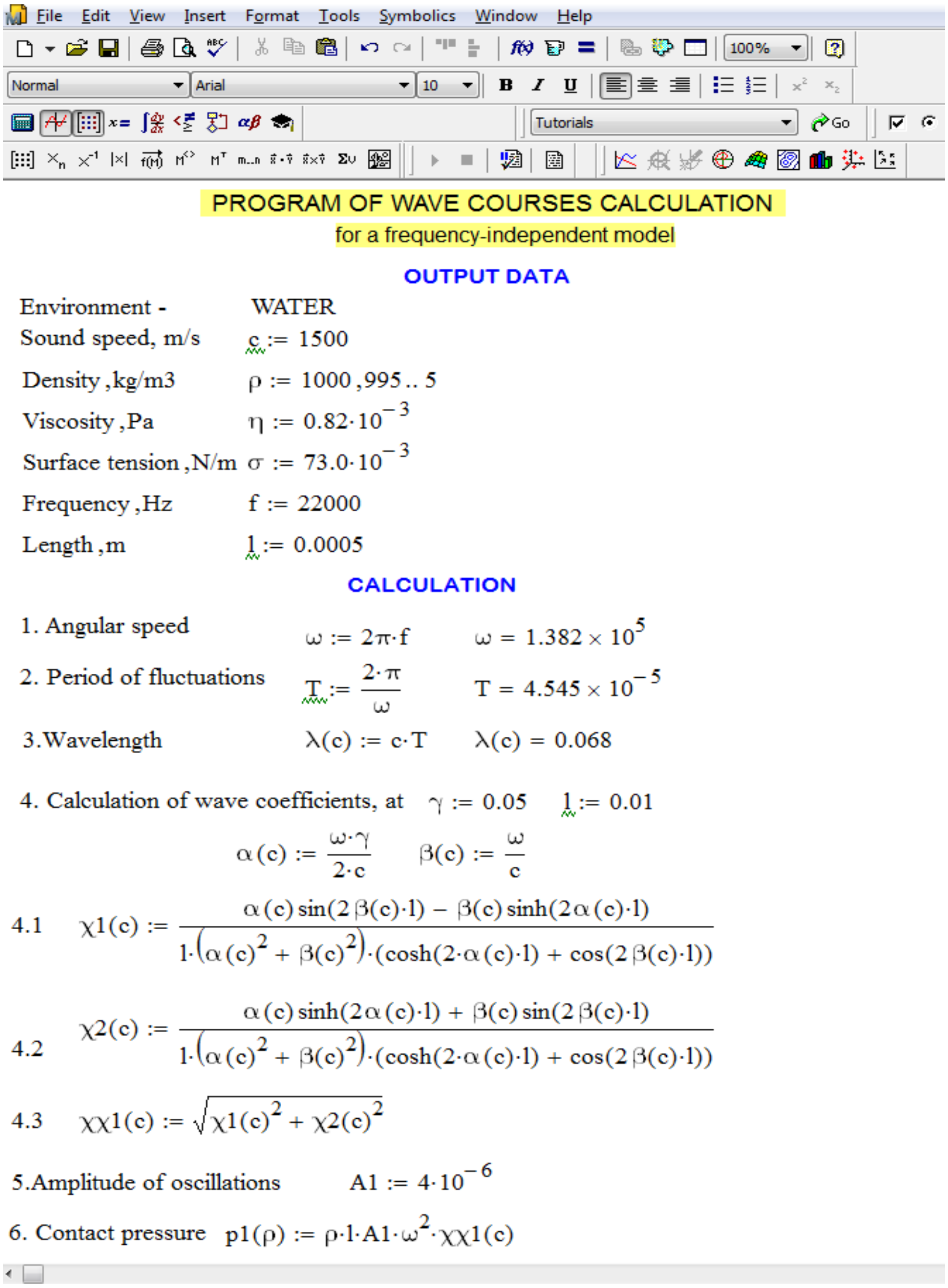
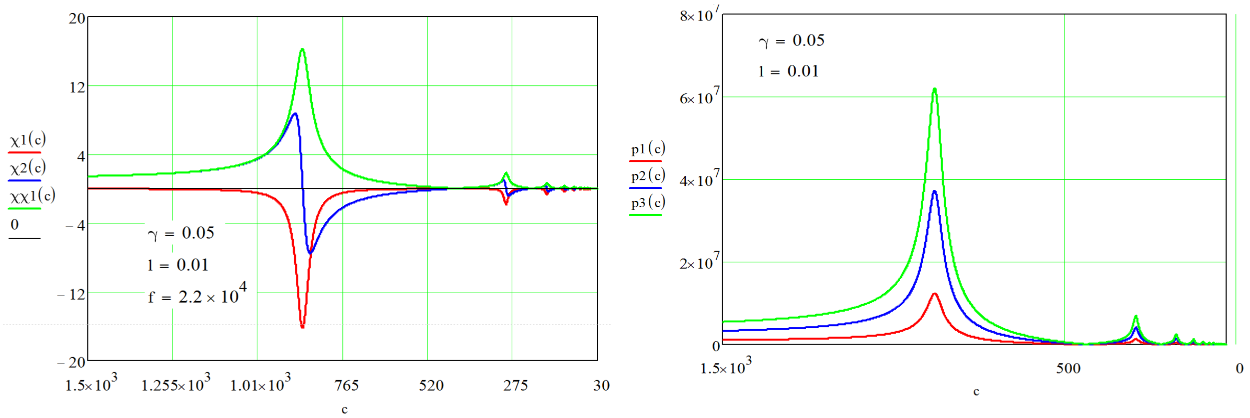


Fig. 3. Algorithm for wave coefficients and contact pressure calculation: 5.1 and 5.2. – analytical expressions of wave coefficients; 5.3 – structural formula of contact pressure

Fig. 4 presented graphs of wave coefficients and contact pressure changes, depending on the change in the velocity of wave propagation at the stages of the origin of the bubbles to the final stage of slamming, where the speed decreased by 50 times. The nature of the wave coefficients variation is worth noting. So, one of the coefficients $\chi^{1(c)}$ (red curve) does not change its sign during all stages of the process. Second wave coefficient $\chi^{2(c)}$ (blue curve) has areas with positive and negative values. Such character of wave coefficients change is an important result of the influence of the active (red curve) and reactive (blue curve) components of the pressure that are included in the overall analytical dependence for determining the contact pressure.

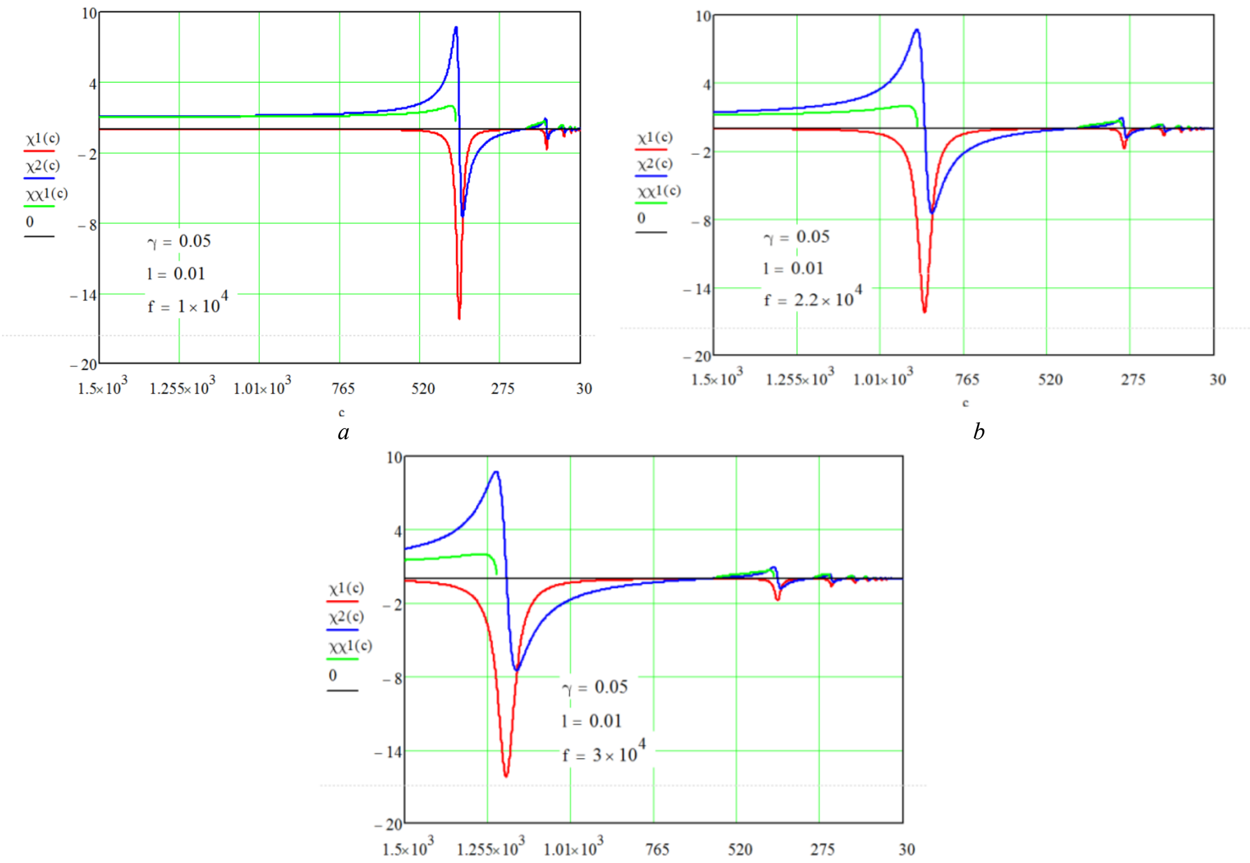


a *b*

Fig. 4. Graphs of changes in wave coefficients (a) and contact pressure (b) depending on the change in the propagation velocity of waves in a gas-liquid medium for three amplitudes of the contact zone variations:

The presence of resonant zones depends on a number of parameters and, in particular, on the characteristic size of the cavitation chamber in the direction of propagation of waves.

The frequency of acoustic action (Fig. 5) significantly influences the nature of the change in wave coefficients.



a *b* *c*

Fig. 5. Influence of oscillations frequency on wave coefficients change: a –10 kHz; b –22 kHz; c – 30 kHz for three amplitudes of the contact zone variations: $A=4.10^{-6}$ m; – $A=12.10^{-6}$ m; – $A=20.10^{-6}$ m

Discussion of results of investigation of the influence of the ultrasound apparatus acoustic parameters and the environment rheological properties on the contact pressure

The research confirms that the key parameter of the gas and air bubbles evolution in the acoustic field is the sound pressure that forms in the contact zone of the acoustic apparatus – environment system. Determining qualitative and quantitative changes in contact pressure is the dominant factor in the reasoning and definition of the environmental processing intensification rational parameters. For the first time, it has been proved (fig. 4 and fig. 5) that choosing a model of the processing environment it is necessary to consider both the reactive and active component of pressure because it characterizes the dissipative properties of the environment.

An important direction for further research is the establishment of an environment dissipative properties functional dependence on their composition, acoustic parameters and the visco-plastic components in the calculation models. The resonant zones presence gives the possibility to use them for optimizing the modes and parameters of the cavitation apparatus; it will intensify the process of processing various environments. Additional studies are required to evaluate the transformation state of the initial environment into the final one (density change); the change in the waves propagation velocity in the environment should be also taken into account. Studies in this area are provided by the program and the evaluation of experimental studies of theoretical dependencies.

Conclusions

1. It was proved that the main characteristics of the power interaction of the ultrasound apparatus and the treated environment are the contact pressure and the propagation speed.
2. The ultrasound apparatus acoustic parameters influence on the rheological properties of the environment on the contact pressure was found. The presence of resonant zones opens the possibility of their real use in optimizing the modes and parameters of the cavitation apparatus; it will intensify the process of processing various environments.
3. An important direction for further research is the establishment of an environment dissipative properties functional dependence on their composition, acoustic parameters and the visco-plastic components in the calculation models.

Дослідження процесів силової взаємодії акустичного апарату із оброблювальним технологічним середовищем

І.М. Берник

Анотація. *Визначена фізична картина процесів взаємодії апарату з оброблювальним технологічним середовищем за умови врахування зміни його реологічних властивостей. Ефективність кавітаційних ефектів від початкового до кінцевого етапу обробки обумовлена контактним тиском та швидкістю його розповсюдження. Врахована низка силових та енергетичних характеристик і параметрів для ефективної реалізації кавітаційного процесу. На базі цих параметрів енергія процесу акумулюється при розширенні бульбашки від початкового врівноваженого до максимального її радіусу. Основу акумуляції складають розтягувальні сили у фазі розрідження акустичної хвилі. Побудовані графіки залежності контактного тиску від ключових параметрів процесу та визначенні закономірності його зміни. Запропоновані режими та параметри протікання енергоефективного акустичного процесу обробки різних середовищ. Визначені напрямки застосування результатів досліджень та їх подальший розвиток.*

<u>Ключові слова:</u> акустичний апарат,кавітаційний процес, взаємодія, енергія, середовище, реологічні властивості, параметри, тиск.

Исследование процессов силового взаимодействия акустического аппарата с обрабатывающей технологической средой

И.Н. Берник

Аннотация. *Определенна физическая картина процессов взаимодействия аппарата с обрабатываемой технологической средой при условии учета изменения его реологических свойств. Эффективность кавитационных эффектов от начального до конечного этапа обработки обусловлена контактным давлением и скоростью его распространения. Учтен ряд силовых и энергетических характеристик и параметров для эффективной реализации кавитационного процесса. На базе этих параметров энергия процесса аккумулируется при расширении пузырьки от начального уравновешенного до максимального ее радиуса. Основу аккумуляции составляют растягивающие силы в фазе разрежения акустической волны. Построены графики зависимости контактного давления от ключевых параметров процесса и определении закономерности его изменения. Предложенные режимы и параметры протекания энергоэффективного акустического процесса обработки различных сред. Определены направления применения результатов исследований и их дальнейшее развитие.*

<u>Ключевые слова:</u> акустический аппарат, кавитационный процесс, взаимодействие, энергия, среда, реологические свойства, параметры, давление.

References

1. Dolinsky, A. and Ivanitskii, G. (2008), *Heat and mass transfer and hydrodynamics in the vapor-liquid dispersion media*. Thermal basics of discrete input pulse energy, Naukova Dumka, Kiev, Ukraine.
2. Dong Chen, Sanjay K. Sharma, Ackmez Mudhoo (2011), *Handbook on Applications of Ultrasound: Sonochemistry for Sustainability*, CRC Press, Florida, USA.

3. Gumerov, N.A. Ohl, C.-D., Akhatov, I.S., Sametov, S. and Khasimullin, M. (2013), "Waves of acoustically induced transparency in bubbly liquids: theory and experiment", *The Journal of the Acoustical Society of America*, vol. 133 no. 5, pp. 3277–3286.
4. Itkulova, Yu. A., Abramova, O. A., Gumerov, N. A. and Akhatov, I. Sh. (2014), "Modeling bubble dynamics in three-dimensional potential flows on heterogeneous computer systems by the fast method of multipoles and the method of boundary elements", Computational methods and programming, vol. 15, pp. 239-257.
5. Du, T. A., Huang, Ch. and Wang, Y. (2016), "Numerical Model for Evolution of Internal Structure of Cloud Cavitation", ISROMAC-2016, *International Symposium on Transport Phenomena and Dynamics of Rotating Machinery*, April, Hawaii, Honolulu, pp. 10–15.
6. Jose-Luis Capelo-Martinez (2009), Ultrasound in Chemistry: Analytical Applications, John Wiley & Sons, New York, USA
7. Feng, H., Barbosa-Cánovas, G.V. and Weiss J. (2011), "Ultrasound Technologies for Food and Bioprocessing," Food Engineering Series, *Springer Science+Business*, New York, USA.
8. Ercan, S.S. and Soysal Ç. (2013) "Use of ultrasound in food preservation", *Natural Science*, vol. 5, pp. 5-13, http://dx.doi.org/10.4236/ns.2013.58A2002
9. Bernyk I. (2017) "Theoretical aspects of the formation and the development of cavitation processes in a technological environment", MOTROL. *Commission of Motorization and Energeticsin Agriculture*, vol. 19, no. 3, pp. 3 – 12.
10. Wood, R. J., Lee, J. and Bussemaker, M.J. (2017), "A parametric review of sonochemistry: Control and augmentation of sonochemical activity in aqueous solutions", *Ultrasonics Sonochemistry*, vol. 38, September, pp. 351-370.
11. Luhovskyi, O., Fesich, V., Zilinskyi, A., and Lavrynenkov A. (2017) "Performance increase of ultrasound liquid sprayers", *Mechanics and Advanced Technologies*, vol. 80, no. 2, pp. 113–122, DOI: 10.20535/2521-1943.2017.80.111878
12. Kleiman, J., Kudryavtsev, Y. and Luhovskyi, O. (2017) "Effectiveness of ultrasonic peening in fatigue improvement of welded elements and structures", *Mechanics and Advanced Technologies*, vol. 81, no. 3, pp. 92–98, DOI: http://dx.doi.org/10.20535/2521-1943.2017.81.117489
13. Khmelev, V.N., Golykh, R.N., Shalunov, A.V., Pedder, V.V., Nesterov, V.A. and Dorovskikh, R.S. (2015), " Evaluation of optimum modes and conditions of contact ultrasonic treatment of wound surface and creation of tools for its implementation", *American Journal of Engineering Research (AJER)*, vol. 4, no. 8, pp. 19-30.
14. Shalunov, A.V., Khmelev, V.N., Golykh, R.N. and Nesterov, V.A. (2017), "Atomization of liquids by ultrasonic", *South-Siberian scientific bulletin*, vol. 20, no. 4, pp. 274–281.
15. Khmelev, V.N., Kuzovnikov, Yu.M. and Khmelev, M.V. (2017), "Ultrasonic devices for scientific researches", *South-Siberian scientific bulletin*, vol. 17, no. 1, pp. 5–13.
16. Gallego-Juarez J.A. (2010), "High-power ultrasonic processing: recent developments and prospective advances", *Physics Procedia,* vol. 3, pp. 35–47, https://doi.org/10.1016/j.phpro.2010.01.006
17. Golykh, R.N., Khmelev, V.N., Khmelev, S.S. and Shalunov, A.V. (2013), "Modes and conditions of efficient ultrasonic influence on high-viscosity media in technological volumes", *14th International Conference of Young Specialists on Micro|Nanotechnologies and Electron Devices. EDM'2013:* Conference Proceedings, Novosibirsk: NSTU, pp. 128–133.
18. Time, R.W. and Rabenjafimanantsoa, A.H. (2011), "Cavitation Bubble Regimes in Polymers and Viscous Fluids", Annual transactions of the Nordic rheology society, vol. 19, 12 p.
19. Khmelev, V., Leonov, G., Barsukov, R., Gypsy, S., and Shalunov, A. (2007), Ultrasonic Multifunctional and Specialized Equipment for Intensification of technological processes in industry, agriculture and households, Publishing House of the Alt. state. tehn. University, Biisk, Russia.
20. Brujan, E.A. and Williams, P.R. (2005), "Bubble dynamics and cavitation in non-newtonian liquids", Reology reviews, The British Society of Rheology, pp. 147-172.
21. Sirotyuk, M. (2008), Acoustic cavitation, Nauka, Moscow, Russia.
22. Agranat, B. (1974), Ultrasonic technology, Metallurgy, Moscow, Russia.
23. Bernyk, I., Luhovskyi, O. and Nazarenko, I. (2016), "Research staff process of interaction and technological environment in developed cavitation", *Journal of Mechanical Engineering NTUU "Kyiv Polytechnic Institute"*, vol. 76, no. 1, pp. 12–19, DOI: https://doi.org/10.20535/2305-9001.2016.76.39735