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PHYSICAL ANALOGUE OF THE PROCESS OF ULTRASONIC LIQUID NEBULIZATION IN A THIN LAYER

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ФИЗИЧЕСКАЯ МОДЕЛЬ ПРОЦЕССА УЛЬТРАЗВУКОВОГО РАСПЫЛЕНИЯ ЖИДКОСТИ В ТОНКОМ СЛОЕ

The paper studies the features of ultrasonic nebulization of the liquid in a thin layer. All existent models of the fracture mechanism of intermolecular bonds in the liquid especially «cavitating», «capillary-wave», «cavitation-wave» while implementation of the process of ultrasonic nebulization of the liquid in a thin layer are shown and analyzed. A model is made taking into account the results of the last known experimental researches which confirm separate assumptions and mechanisms of realization of process of ultrasonic nebulized. The results of own experimental researches of authors are presented, in particular presented pictures of surface of layer of liquid on the vibrating surface of dispersing agent to form capillary waves, which allowed to confirm the known analytical dependences, and pictures of influence of form of surface of nebulized, on an aerosol torch. Represented a renewed physical analogue of the process of ultrasonic liquid nebulization in a thin layer.

Keywords: ultrasonic nebulization, dispersing agent, a thin layer of liquid, physical analogue.

Introduction

Many industries require the implementation of the high-efficient production processes of the fine aerosol. In the first places are chemical industry, radioelectronics, heat power, engineering and instrument-making industries, food-manufacturing industry, medicine and agricultural industry. All of these industries are based on the usage of a wide range of technological processes with liquid aerosol. However to improve the efficiency of these processes should be fully and authentically represent the represent the physics of the process of ultrasonic nebulization. By reason of complete imagination of the physics process can be determined the influence of different factors on the dispersion characteristics of aerosol and formation processes of the aerosol flare.

For example, in such a way the efficiency of the engine operation depends on the proper preparation of the fuel-air mixture, which in turn should have a dispersion of 50 ... 150 mym operating with a fuel carburetor system and 15…60 mym operating with point or separation system of fuel injection with a help of electromagnetic injectors [1, 2]. Relative to the medicine the alveolus and bronchiole lungs treatment which is maximally efficiently reached with the dispersion of medicine aerosol 0,5…10 mym while the range for the respiratory passages is by order of magnitude greater (10…30 mym) [3]. There is a demand of forming synthetic microclimate for the humidity support in the premises in agricultural and food-manufacturing industries [4].

So, current industry conditions demand the raise of efficiency of one or another process with the usage of liquid fine aerosol. In its turn this imposes high requirements for the usage of liquid spraying devices that stimulate the exact understanding of the physics of the ultrasonic nebulization process in order to provide the requirement dispersion, productivity and the aerosol flare pattern as well as electronic operation speed management.

The object of the article is the development of a physical model of ultrasonic nebulization process in the thin layer to determine the possibilities of aerosol quality improvement and expanding the limits of the parameters monitoring.

The main part

There are several model variants of fracture mechanism of intermolecular bonds in the liquid in the implementation process of ultrasonic nebulization in a thin layer.

Thus, the known «cavitation» model that emerged as a result experimental researches carried out Zolterom [5, 6]. According to this hypothesis, the formation finely dispersed aerosol is realized by the result of shock waves when take a place slamming of cavitation bubbles close to the atomization surface.

However in such a model droplets of different size should have to come off the liquid surface due to the microexplosions. But when atomization in the thin layer takes a place there can be observed an aerosols similar to monodisperse one [7]. In addition, the explosive atomization droplets of liquid should have to scatter randomly in different directions. But we observe quite an ordered motion of droplets in the normal direction to the surface sputtering.

The second variant of a physical model is a «capillary-wave» model established by such scholars as Biza, Dirnahl and Eshe [8]. According to this model, liquid nebulization is made due to the infusion of the ultrasonic vibrations into the thin layer of liquid that is caused the standing capillary waves of finite amplitude on the shaking liquid surface. At capillary waves peaks failure due to the loss of the stability are formed aerosol droplets which are close to monodisperse ones.

But the analysis of the results of experimental research of aerosol dispersion in the nebulization flare indicates the availability of individual droplets, which significantly differ from the basic monodisperse size [9]. Nevertheless, this indicates the existence of cavitative explosive kick fluids from the surface.

The next variant of the model is established by the Boguslavsky, Eknadiosyants [10] and Antonovych [11], according to the authors it is a compromise between the first two and is called «cavitation-wave». The offered model is based on the fact that sputtering takes place according to the following mechanisms:

- destruction of resonant gas-vapor bubbles that flutter at the liquid surface;
- slamming of cavitation bubbles close to the surface the liquid generating shock waves;
- detachment droplets of the liquid from the surface by its perturbations in the process of gas-vapor bubbles oscillation;
- due to intense pulsating movements of gas-vapor bubbles at the atomization surface the loss of capillary waves stability with the formation of the peaks from which monodisperse aerosol droplets fall down;
- the formation of capillary waves in the absence of the fluttering bubbles with peaks from which aerosol droplets break away.

«Capillary-wave» model has become the most popular and has been specified by many authors such as Polman, Lirke [12] Folher, Tmmerhaus [13] Lugovsky [14] Khmelev [15] Shalunov [16] and others.

Interesting results of experimental physics research process of ultrasonic nebulization in the thin layer were got by Shalunov in his work [16]. He suggested confirming the presence and expression of cavitation in the process of nebulization in the thin liquid layer on the fact and degree of cavitation erosion of material of which is made a working vibrating surface of dispersing agent. The experiment was that on the working surface of titanium dispersing agent was conducted the high quality reclaimed liquid. Through studies of produced aerosol with the involvement of high-precision equipment was found that after ultrasonic nebulization in the thin layer there can be seen elements that are components a titanium alloy. This indicates the presence of cavitation erosion of vibrating surface of dispersing agent. That is required experiment confirms the presence of cavitation in the process of ultrasonic nebulization in a thin layer.

Analyzing the new obtained results can be suggested a specification of a physical model of the process of ultrasonic nebulization of liquids in the thin layer that takes into account the proven presence of cavitation processes but in a kind of new viewing.

The implementation of ultrasonic atomization of liquids occurs due to the injection of alternating electric signal on the piezoelectric transformer that excites standing longitudinal vibrations in the resonant system of dispersing agent [17]. In this case the atomization surface is placed in the antinode of wave movement. To achieve amplitude of oscillation required for the start of nebulization process are used particle velocity sonorous transformers. The liquid which is delivered on the atomization surface covers it with a 0,3…1mm thick layer.

It should be noticed in the process of ultrasonic vibrations perturbation in the resonance system of dispersing agent the strength of surface friction force of liquid reduces and under the action of cohesion force the liquid collects in the droplet. At small amplitude of oscillations of the vibrating surface of dispersing agent a liquid layer moves as a single unit with the vibrating surface (Fig. 1). With an increase of the amplitude of oscillations due to the inertia characteristics of the liquid there are formed standing capillary waves on its surface as evidenced by nebulosity of liquid layer (Fig. 2).

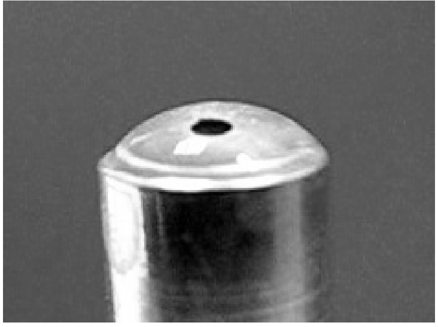


Fig. 1. Atomization surface, which is vibrates with a small amplitude and is covered with a liquid layer

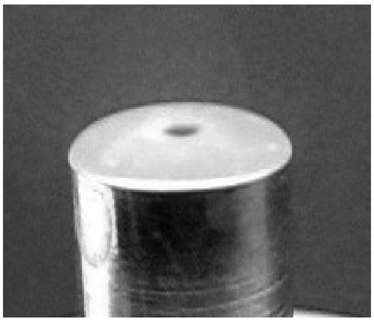
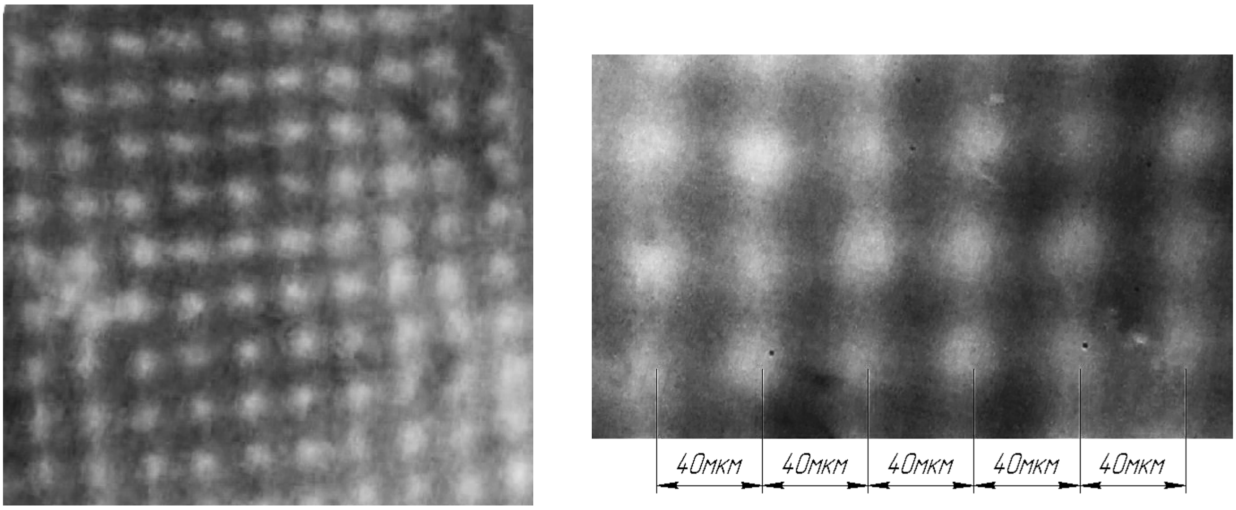


Fig. 2. Atomization surface with a liquid layer at the moment of capillary waves formation

The frequency of capillary waves is half as much as the excitation frequency of dispersing agent [7] (Fig. 3a). Capillary waves are uniformly located on the liquid surface (Fig. 3b). With the use of created acoustic-optical installation was managed to confirm experimentally 94-96% accuracy of known [7] analytical dependence for calculating the length of capillary waves:

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



а

б

Fig. 3. Location of capillary waves on the vibrating surface for $\sigma = 72{,}86 \cdot 10^{-3}\, N/m$; $\rho = 1000 kg/m^3$; $f = 60kHz$ (*a* – increase in 24 times; *b* – increase in 35 times)

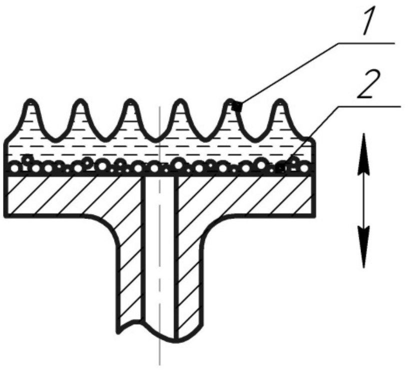


Fig. 4. Scheme of the formation of capillary waves and cavitation layer by atomization in the thin layer (1 – capillary waves; 2 – cavitation layer)

With further increase in the amplitude of oscillation of the working surface of dispersing agent cavitation layer begins to form at the emitting surface (Fig. 4). Certain movement inertia of the cavitation bubble [18] helps to maintain and partly increase capillary waves. With slamming of cavitation bubble near the "solid" boundary there are formed strong cumulative jets directed sideways of the "solid" surface and cause the destruction of emitting surface of dispersing agent that is cavitation erosion.

A cumulative jet arises towards the “solid” boundary with every slamming of cavitation bubble close to the “solid” boundary it means that because of the repeated impact action of these jets onto the surface [19, 20]. At the expense of intensive microflows that are existed in the time of oscillations and slamming of cavitation bubbles, liquid is moved and uniformly saturated with dispersed by material particles of the atomization surface of dispersing agent. In this case the fluid mass is scaled up and as well as the inertia of the liquid and that intensifies lifting capillary waves. The emerging cavitation bubbles transform the liquid layer into biphasic one resulting in a decrease of the surface liquid tension.

Fig. 5. Destruction of the capillary wave with breaking droplets away

When dispersed metal particles of the emitting surface of dispersing agent reach while stirring the surface of liquid layer they disrupt its entirety that also leads to reduction of surface tension force and additional intensification of the nebulization process. If the surface tension forces are unable to maintain the integrity of the stretched capillary wave its comb is destroyed and an aerosol droplet breaks away of it (Fig. 5).

Aerosol droplets being broken away in the dynamic process of capillary wave lifting and which have a certain mass due to this process fly away in capillary wave direction that is orthogonal to the atomization surface (Fig. 6a). The kinetic energy that is possessed in this case by the droplet allows it to fly forwarded a certain distance, in other words to generate an aerosol flame required for this technological process (Fig. 6b, 6c).

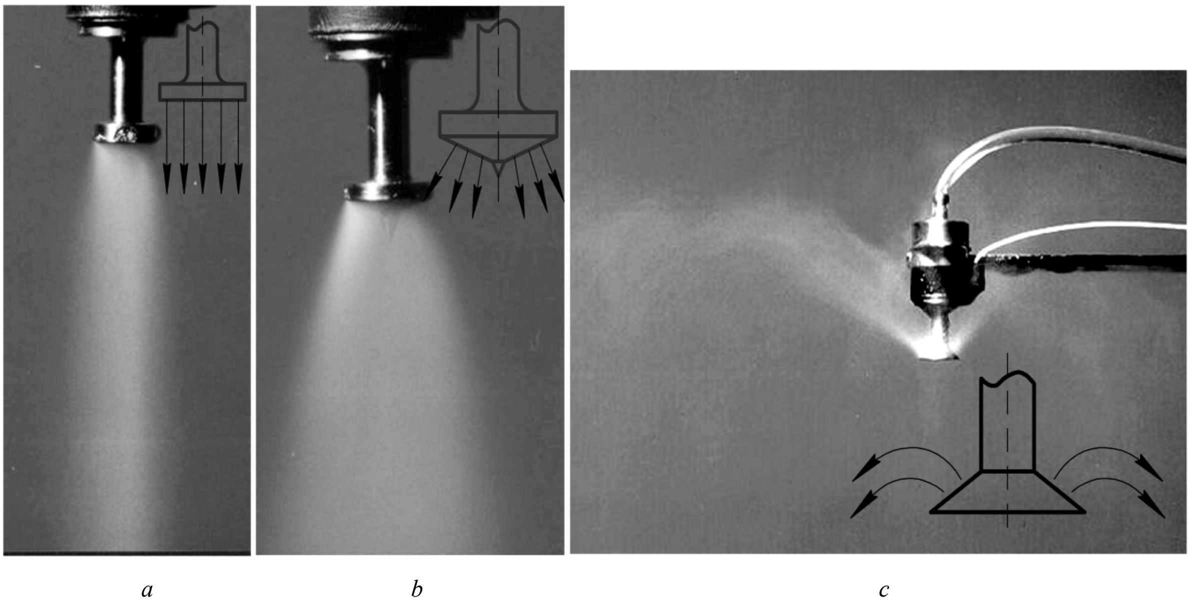

a b c

Fig. 6. Aerosol flame patterns due to nebulization process in the thin layer from the different surfaces (*a* – flat surface; *b* – tapered surface; *c* – reverse tapered surface)

Experimental investigation of derived aerosol dispersion [14] indicates the presence of some deviation from the mono-dispersion that negatively affects the quality of aerosol does not allows to apply the some way of nebulization in technological processes with high requirements concerning the aerosol mono-dispersion. Deviation from the mono-dispersion occurs mostly on the perimeter of the liquid layer. In case if there is a little liquid and at the expense of cohesive force it is getting together into the large liquid stain quickly drifting on vibrating surface of dispersing agent in consequence of friction force reduction, the cavitation layer leads to explosive different-sized liquid droplets emission on the perimeter of the stain where it is most close to the liquid surface with generated capillary waves providing the mono-dispersion aerosol production.

If there is enough liquid on the vibrating surface of dispersing agent for its complete coverage, generally the different-sized aerosol is originated on the perimeter of the atomization surface. Therefore it is desirable to achieve the reduction of the probability of cavitation layer approximation to the liquid surface by constructive means.

The part of the of ultrasonic energy injected into a thin layer considering coefficient of liquid surface reflection gets into the space where atomization is carried out superposing minor pulsations onto the aerosol flame.

The conclusions

In authors' opinion, the described physical model is the closest model to the real reflection of ultrasonic nebulization mechanism in a thin layer among the known ones. The use of the proposed model will facilitate the expansion of possibilities of ultrasonic nebulization process regulation in order to obtain the liquid aerosol with predetermined characteristics.

Анотація. *Розглянуті особливості ультразвукового розпилення рідини в тонкому шарі. Висвітлені та проаналізовані всі існуючі, а саме «кавітаційна», «капілярно-хвильова», «кавітаційно-хвильова», моделі механізму руйнування міжмолекулярних зв'язків в рідині при реалізації процесу ультразвукового розпилення рідини в тонкому шарі. Модель складена з урахуванням результатів останніх відомих експериментальних досліджень, що підтверджують окремі припущення та механізми реалізації процесу ультразвукового розпилення. Представлені і результати власних експериментальних досліджень авторів, зокрема представлені фотографії поверхні шару рідини на вібруючій поверхні диспергатора з утворенням капілярних хвиль, що дозволило підтвердити відомі аналітичні залежності, та фотографії впливу форми поверхні розпилення на аерозольний факел. Представлена оновлена фізична модель процесу ультразвукового розпилення рідини в тонкому шарі.*

Ключові слова: *ультразвукове розпилення, диспергатор, тонкий шар рідини, фізична модель.*

Аннотация. *Рассмотрены особенности ультразвукового распыления жидкости в тонком слое. Освещены и проанализированы все существующие, а именно «кавитационная», «капиллярно-волновая», «кавитационно-волновая», модели механизма разрушения межмолекулярных связей в жидкости при реализации процесса ультразвукового распыления жидкости в тонком слое. Модель составлена с учетом результатов последних известных экспериментальных исследований, подтверждающие отдельные предположения и механизмы реализации процесса ультразвукового распыления. Представлены и результаты собственных экспериментальных исследований авторов, в частности представлены фотографии поверхности слоя жидкости на вибрирующей поверхности диспергатора с образованием капиллярных волн, что позволило подтвердить известные аналитические зависимости, и фотографии влияния формы поверхности распыления на аэрозольный факел. Представлена обновленная физическая модель процесса ультразвукового распыления жидкости в тонком слое.*

Ключевые слова: *ультразвуковое распыление, диспергатор, тонкий слой жидкости, физическая модель.*

1. *Васильєв С.Н.* Двигатели внутреннего сгорания / С.Н. Васильєв. – М.: Машиностроение, 1995. – Т.1. – 290с.
2. *Луговской А.Ф.* Системы подготовки топливно-воздушной смеси с ультразвуковыми диспергаторами / А.Ф. Луговской // Праці Міжнародної науково-технічної конференції "Прогресивна техніка і технологія машинобудування, приладобудування і зварювального виробництва". – 1998. – Том III. – С. 293-299.
3. *Луговской А.Ф.* Возможности получения мелкодисперсного аэрозоля в медицинских інгаляторах / А.Ф. Луговской, В.И. Чорный, Н.В. Чухраев, А.В. Мовчанюк // Вестник Национального технического универсистета Украины „КПИ”. Машиностроение. – 2000. - Вып.38. - С. 163-168.
4. *Ляшок А.В.* / Ультразвукове розпилення рідини у мехатронних системах штучного мікроклімату / А.В. Ляшок, О.Ф. Луговський // Всеукраїнський науково-технічний журнал «Промислова гідравліка і пневматика» – №4 (34)’2011. – С. 20– 25.
5. *Физика* и техника мощного ультразвука. Том I. Источники мощного ультразвука / Под ред. Л.Д. Розенберга – М.: Наука, 1967. – 380 с.
6. *Физика* и техника мощного ультразвука. Том III. Физические основы ультразвуковой технологии / Под ред. Л.Д. Розенберга – М.: Наука, 1970. – 688 с.
7. *Экнадиосянц О.К.* Получение аэрозолей / О.К. Экнадиосянц. - В кн.: Физические основы ультразвуковой технологии. Под ред. Л.Д. Розенберга. - М.: Наука, 1970. - С. 339-392.
8. *Bisa K.* Zerstaubung von Flussigkeiton mit Ultraschall. / K. Bisa, K. Dirnagl, R. Esche - Siemens Z., – 1954. – 28, 8, 314.
9. *Луговський О.Ф.* Підвищення ефективності апаратних засобів для реалізації ультразвукових кавітаційних технологій: дис. доктора тех. наук: 05.05.13 / Луговський Олександр Федорович. – К., 2005. – 273 с.
10. *Богуславский Ю.Я.* О физическом механизме распыления жидкости акустическими колебаниями / Ю. Богуславский, О. Экнадиосянц. – Акуст. ж., 15 вып. 1, 17, 1969.
11. *Antonewich J.N.* Ultrasonic Atomisation of Liquids. / J.N. Antonewich. – Proc. Nat. Electronics Conf. Chicago, 1957. – 13, 798
12. *Portman R.* Zur Flüssigkeitsvernebelung mit Ultraschall unter besonderer Berücksichtigung der Aerosolerzeugung / R. Portman, E.G. Lierke. – Congres International d‘Acoustique, Liege, 1965. D35
13. *Fogler H.S.* Ultrasonic Atomization Studies / H.S. Fogler, K.D. Timmerhaus. – JASA, 39, №3’1966. – 515
14. *Луговской А.Ф.* Ультразвуковая кавитация в современных технологиях / А.Ф. Луговской, Н.В. Чухраев. – К.: Видавничо-поліграфічний центр «Київський університет», 2007. – 244 с.
15. *Хмелев В.Н.* Ультразвуковое распыление жидкостей: монография / В.Н. Хмелев, А.В. Шалунов, А.В. Шалунова. – Бийск: Изд-во Алт. гос. техн. ун-та, 2010. – С. 22-36
16. *Шалунов А.В.* Исследование процесса и разработка аппаратов ультразвукового диспергирования жидкостей: дис. канд.тех.наук: 05.17.08 / Шалунов Андрей Викторович. – Бийск, 2006. – 153 с.
17. *Ляшок А.В.* / Методика розрахунку ультразвукового диспергатора для розпилення в тонкому шарі / А.В. Ляшок // Всеукраїнський науково-технічний журнал «Вібрації в техніці та технологіях» – 2012. – Вип. 1(65).- С. 15-20
18. *Лаутерборн В.* Неустановившиеся течения воды с большими скоростями / Под. ред. Л.И. Седова и Г.Ю.Степанова. - М., 1973. - С. 267-275.
19. *Айвэни Р.Д.* Теоретические основы инженерных расчетов / Р.Д. Айвэни, Ф.Г.Хэммит, Т.М. Митчелл – 1966. - Т. 88. - № 3. - С. 124-133.
20. *Ноде С.Ф.* Техническая механика / С.Ф. Ноде, А.Т. Эллис – 1961. - Т. 83. - № 4. - С. 204-212.

REFERENCES

1. *Vasil'єv S.N.* Dvigateli vnutrennego sgoranija [Internal combustion engines]. Moscow: Mashinostroenie, 1995. T.1. 290 p.
2. *Lugovskoj A.F.* Sistemy podgotovki toplivno-vozdushnoj smesi s ul'tpazvukovymi dispepgatopami. Ppaci Mizhnapodnoï naukovo-tehnichnoï konfepencïï "Ppogpesivna tehnika i tehnologija mashinobuduvannja, ppiladobuduvannja i zvapjuval'nogo vipobnictva". 1998. Tom III. pp. 293-299.
3. *Lugovskoj A.F.,* Chornyj V.I., Chuhraev N.V., Movchanjuk A.V. Journal of Mechanical Engineering of NTUU «KPI». 2000. no.38. pp. 163-168.
4. *Ljashok A.V.,* Lugovs'kij O.F. Ul'trazvukove rozpilennja ridini u mehatronnih sistemah shtuchnogo mikroklimatu. Vseukraïns'kij naukovo-tehnichnij zhurnal «Promislova gidravlika i pnevmatika» no 4 (34)’2011. pp. 20– 25.
5. *Fizika* i tehnika moshhnogo ul'trazvuka [Physics and technology of high-intensity ultrasound]. Tom I. Istochniki moshhnogo ul'trazvuka. Pod red. L.D. Rozenberga. Moscow: Nauka, 1967. 380 p.
6. *Fizika* i tehnika moshhnogo ul'trazvuka [Physics and technology of high-intensity ultrasound]. Tom III. Fizicheskie osnovy ul'trazvukovoj tehnologii. Pod red. L.D. Rozenberga. Moscow: Nauka, 1970. 688 p.
7. *Jeknadiosjanc O.K.* Poluchenie ajerozolej [The resulting aerosol]. V kn.: Fizicheskie osnovy ul'trazvukovoj tehnologii. Pod red. L.D. Rozenberga. Moscow: Nauka, 1970. pp. 339-392.
8. *Bisa K.,* Dirnagl K., Esche R. Zerstaubung von Flussigkeiton mit Ultraschall. Siemens Z., 1954. 28, 8, 314.
9. *Lugovs'kij O.F.* Pidvishhennja efektivnosti aparatnih zasobiv dlja realizacïï ul'trazvukovih kavitacijnih tehnologij: dis…doktora teh. nauk: 05.05.13 / Lugovs'kij Oleksandr Fedorovich. Kyiv, 2005. 273 p.
10. *Boguslavskij Ju.Ja.,* Jeknadiosjanc O. O fizicheskom mehanizme raspylenija zhidkosti akusticheskimi kolebanijami. Akust. zh., 15 vyp. 1, 17, 1969.
11. *Antonewich J.N.* Ultrasonic Atomisation of Liquids. Proc. Nat. Electronics Conf. Chicago, 1957. 13, 798
12. *Portman R.,* Lierke E.G. Zur Flüssigkeitsvernebelung mit Ultraschall unter besonderer Berücksichtigung der Aerosolerzeugung. Congres International d‘Acoustique, Liege, 1965. D35
13. *Fogler H.S.,* Timmerhaus K.D. Ultrasonic Atomization Studies. JASA, 39, no 3’1966. 515
14. *Lugovskoj A.F.,* Chuhraev N.V. Ul'trazvukovaja kavitacija v sovremennyh tehnologijah [Ultrasound kavytatsyya in modern technology]. Kyiv: Vidavnicho-poligrafichnij centr «Kiïvs'kij universitet», 2007. 244 p.
15. *Hmelev V.N.,* Shalunov A.V., Shalunova A.V. Ul'trazvukovoe raspylenie zhidkostej: monografija [Ultrasonic atomization of liquids]. Bijsk: Izd-vo Alt. gos. tehn. un-ta, 2010. pp. 22-36
16. *Shalunov A.V.* Issledovanie processa i razrabotka apparatov ul'trazvukovogo dispergirovanija zhidkostej: dis…kand.teh.nauk: 05.17.08 / Shalunov Andrej Viktorovich. Bijsk, 2006. 153 p.
17. *Ljashok A.V.* Metodika rozrahunku ul'trazvukovogo dispergatora dlja rozpilennja v tonkomu shari. Vseukraïns'kij naukovo-tehnichnij zhurnal «Vibracïï v tehnici ta tehnologijah». 2012. Vip. 1(65). pp. 15-20
18. *Lauterborn V.* Neustanovivshiesja techenija vody s bol'shimi skorostjami [Unsteady flow of water at high speeds]. Pod. red. L.I.Sedova i G.Ju.Stepanova. Moscow, 1973. pp. 267-275.
19. *Ajvjeni R.D.,* Hjemmit F.G, Mitchell T.M. Teoreticheskie osnovy inzhenernyh raschetov [Theoretical basis of engineering calculations]. 1966. T. 88. no 3. pp. 124-133.
20. *Node S.F.,* Jellis A.T. Tehnicheskaja mehanika [Technical Mechanics]. 1961. T. 83. no 4. pp. 204-212.