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N. P. KHRUNINA[1], Leading Researcher, Candidate of Engineering Sciences, npetx@mail.ru
A. Yu. CHEBAN[1], Leading Researcher, Associate Professor, Candidate of Engineering Sciences

[1]Khabarovsk Institute of Mining, Khabarovsk Federal Research Center, Far East Branch, Russian Academy of Sciences, Khabarovsk, Russia

A THEORETICAL APPROACH TO DISINTEGRATION EQUIPMENT DESIGN FOR MINERAL RAW MATERIALS

The article discusses prospects of research aimed at the use of nonconventional methods of energy deposition on mineral media and hydrodynamic influence on the processes of dispersion of solid particles in liquids. Spotlight is on rotary machines and plants using hydrodynamic ram phenomenon. It is established that the theory related to cavitation lacks sufficient development to be used in engineering and design of such machines. The conventional design is based on determining the geometric parameters of the flow of working members and hydrodynamic characteristics, including pressure and flow rate. The purpose of the study is to analytically determine the influence exerted by speed modes and volumetric flow rate of hydromixes on thermodynamic and structural changes in the system during destruction of mineral components at the first stage of microdisintegration in a new-type hydrodynamic generator. Based on process modeling, it is found that the governing part in dynamic eddy effects in the flow energy transformation belongs to the exposure time with regard to the thermodynamic potential of the system, subject to the volumetric flow rate, velocity and pressure of the hydromix jet. With an increase in the exposure time by two times and in the flow rate of the hydromix by five times, at the minimum content of the solid phase in the hydromix, the increment in the specific interphase surface of the mineral component reaches two orders of magnitude. The diagram of the proposed plant with a diffuser, two cone dividers with blades and inclined helix surfaces is considered. The advantage of such plants is a significant reduction in energy costs due to elimination of rotating parts. The development of theoretical, numerical and experimental methods for the study and engineering of gravity machines based on hydrodynamic phenomena and cavitation will make it possible to design adaptable pilot plants suitable for operation at mining facilities.

Keywords: *high-clay sands, hydrodynamic effect, dispersion, disintegration, speed, jet pressure, thermodynamic potential, specific interphase surface*

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In processing of minerals, including gold-bearing sand, the critically important process is disintegration which is to ensure complete dissociation of aggregates into free grains for their further separation with regard to physical and chemical properties [1–5]. Mining of high-clay sands from placers and sand transportation to processing sites uses different mining-and-hauling machines, in particular wheel scrapers equipped with loading aids [6, 7]. The field of research of nonconventional methods is being expanded, including mineral processing via treatment by ultrasound or accelerated electron flow; electro-hydrodynamic and pulsed magnetic treatment (PMT); effects of ultrahigh frequencies or high-power nanosecond electromagnetic pulses (PEMP); electrochemical, photon and electro-impulse treatment. Extractability of fine and very fine gold by centrifugal concentration is investigated in the conditions of gold recovery [8, 9]. With a view to assessing prospects for using energy deposition in ore pretreatment, it is attempted to analyze the known nonconventional methods of mineral processing which are targeted at enhanced disintegration of fine-dispersed granular aggregates and extraction of micro and nano particles of noble metals in the further hydrometallurgy and gravity processes [10, 11].

The known technologies include gold adsorption by coal, treatment by chemically active substances, for instance, sodium halide and sodium hexametaphosphate for gold particles 0.071 mm in size, and subsequent hydrocycloning [12–15]. The Japanese and Chinese researchers propose interesting approaches to the analysis of the acoustic and hydrodynamic cavitation prospects. The lab-scale operation of an acoustic cavitator in production of metals, metal oxides, chalcogenides, metal carbides and carbon is discussed. However, industrial use of cavitators is complicated by the problems connected with scaling [16–19]. Emphasis is laid on the need to develop theoretical, computational and experimental methods to study cavitation generation mechanism for the experimental visualization of particles and flows. The universal methods of R&D, the law of scaling and the optimization techniques are yet to be created in this field of science [20].

The fields of research connected with hydrodynamic effects on dispersed media are being developed. The physical and mechanical model of processes in super cavitation machines is discussed in [21]. It is highlighted that in dispersion of solid elastic particles in liquids, the governing factor is the hydrodynamic penetration of a cumulative micro jet in a material. The particle disintegration efficiency depends on the invasion depth of the jet, on the particle size and on the exposure time. It is proposed to analyze cavitation in terms of mechanical impact, without regard to the other chemical, thermal, electrical etc. factors. It is indicated that the design of a cavitation machine uses determination of the parameters of flow around working members and the hydrodynamic characteristics including flow rate and pressure.

In pursuance of this trend line, A. M. Balabyshko and V. F. Yudaev analyzed the criteria of Zhukovsky, homochromicity and Stukhal [22]. It is suggested to estimate cavitation with regard to the radial flow rate and to the translational velocity of rotor. Considering a rotary device behavior, the squared maximum of the critical speed and the amplitude of the critical impact pressure are correlated using the cavitation criterion.

The hydrodynamics and cavitation phenomena in rotary machines are discussed in terms of pulsed hydrodynamic cavitation in stimulation of mass transfer processes [23].

The dependence of the sound pressure generated by a rotary machine on the radial velocity in the stator channel is presented, and the hydrodynamic cavitation criterion is given by:

$$X = 2P_s / (p < v >^2),$$

where P_s is the liquid pressure at the bubble interface, Pa; p is the density of the medium, kg/m^3; $<v>$ is the average liquid velocity in one channel of the stator, m/s:

$$< v >= [(Q / S_s z_s)^2 + wR^2]^{0.5},$$

where Q is the volume flow rate through the machine, m^3/s; S_s is the cross-section area of a stator channel, m^2; z_s is the number of channels in the stator; w is the rotation speed of the rotor, m/s; R is the outside radius of the cylindrical rotor, m. The Stiles cavitation factor [24] is compared with the proposed hydrodynamic cavitation criterion within the framework of the machine under discussion.

The models of a direct-flow hydrodynamic emitter and of a transduce with the axially symmetric nozzle and obstruction were studied by O. V. Sukharkov

[25] and by Yu. M. Dudzinskiy and A. F. Nazarenko [26]. The formula was obtained for calculating the base frequency of vibrations generated by the direct-flow emitter with regard to the bulk elasticity modulus of liquid [25], and the acoustic output was determined with regard to the sound pressure amplitude, the cavitation domain center–hydrophone distance, density of the medium and the sound velocity in the medium [26].

It is interesting to discuss hypotheses on erosion of materials in hydrodynamic and acoustic cavitation. One hypothesis tells on fatigue failure as a result of induced vibrations of particles under the action of periodic forces. The other hypothesis is connected with an incubation period of plastic deformation [27]. However, these hypotheses cover machine parts made of steel and lead. The study of rocks should take into account the water-proof bonding of clay components and the stiff crystallization of minerals [28]. At the present day, the theory connected with rock fracture under cavitation effects lacks sufficient development to be used in design and engineering of hydrodynamic facilities [29]. In view of these circumstances, we limit ourselves to a theoretical discussion of destruction of mineral components in hydromixes under activated pulsed effect of high-velocity flow in enclosed test facilities.

The aim of this research is to analyze changes in the structure of the solid ingredient in hydromixes for extraction of valuable mineral components in design of destructing members (internal envelope and reflection surfaces meant to modify hydrodynamic parameters of hydromix flow, including velocities, and to generate eddies and hydraulic impacts) in a new-type hydrodynamic generator, with regard to the thermodynamics alterations, velocities and bulk flow rates in the system based on the analytical estimations.

Results and discussion

The research into dissociation of high-clay sands with the increased content of fine and undersize particles of valuable components address the physical, mechanical, physicochemical and hydrodynamic phenomena in interaction of hydromix with working members of equipment with adjustment of outflow in accordance with the preset parameters. In this case, the strength loss takes place under the hydrodynamic effects which initiate reduction in the free surface energy of a solid. The design of the new-type hydrodynamic generator to ensure dissociation of clay and mineral components toward enhanced extraction of valuable mineral fines is discussed in terms of a diagram of a plant with diffusor 1 with nozzle 2 to generate high-velocity jet toward the flat surface of a divider (**Fig. 1**).

Hydromix comes to the upper flat surface 3 of the cone divider 4 with the stiff blades 5 for the flow destruction. Figure 1 (A view) shows the upper surface 3 of the cone divider 4 and the upper surface 6 of the second cone divider 7, which is set below along the pin 8, with the stiff blades 9. From the mathematical formulas (1)–(6), we determine the changes in the thermodynamic system potential dE and in the specific particle interphase area S_{ip} as functions of the hydromix flow rate Q under the action of the flow eddying at the first stage of the hydrodynamic generator. The developed mathematical model of formation of mineral fines in hydromix under hydrodynamic impact of jet on flat surface is described by the relation:

$$S_{ip} = S_{ip0} exp\left(npd_{eddy}Q \cdot VS_{eddy}^{-1}\sigma^{-1}t\right). \quad (1)$$

The initial particle interphase area is assumed to be $S_{ip0} = 1.345 \cdot 10^5$ m^{-1} from the lab-scale tests on comparison of mechanical and ultrasound cavitation results. The generator efficiency n is adopted as 0.5. The solid content of hydromix is assumed to be minimal, i.e., 0.1 of solid and 0.9 of water. The bulk uniform density p of hydromix is 1076.3 kg/m^3. The hydromix flow rate Q is assumed to range from 1.2 to 6 m^3/h. The jet velocity V is found as function of the flow rate Q and the nozzle exit diameter d from the formula:

$$V = 4Q / (3.14d^2). \quad (2)$$

The nozzle exit diameter d is assumed to be 0.02 m. The eddying surface area S_{eddy} at the radius of 0.1 m is:

$$S_{eddy} = 3.14 \cdot 0.1^2 = 0.0314\,m^2. \quad (3)$$

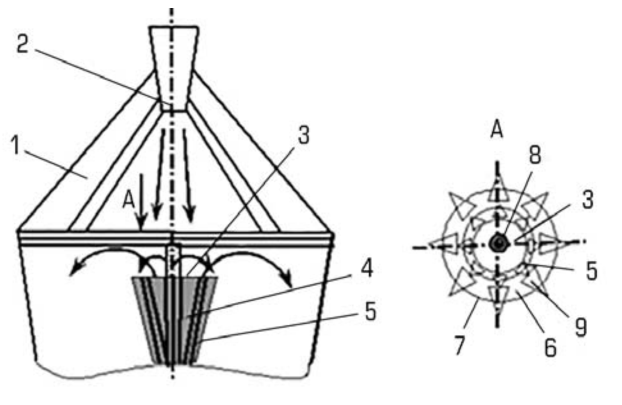

Fig. 1. Diagram of hydrodynamic perturbation initiation at the first generator stage:

1—diffusor; 2—nozzle; 3, 6—flat dividers; 4, 7—cone dividers; 5, 9—blades of dividers; 8—center support pin for working members

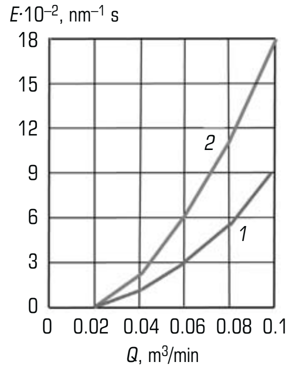

Fig. 2. Hydrodynamic potential of particle surface versus hydromix flow rate at exposure times of 2 s (*1*) and 4 s (*2*)

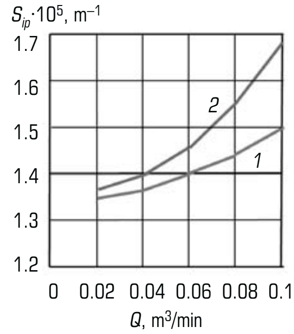

Fig. 3. Specific particle interphase area versus hydromix flow rate at exposure times of 2 s (*1*) and 4 s (*2*)

The specific surface energy σ of particles is known and equals $780 \cdot 10^{-7}$ J/cm^2 = $780 \cdot 10^{-3}$ J/m^2. The varied input parameter of the exposure time t is 2 and 4 s. The product of the density p, bulk flow rate Q and velocity V of hydromix governs the force P applied to mineral particles at the flow obstruction surface:

$$P = pQV, \quad (4)$$

and the relation of the force P and the eddying surface area S_{eddy} governs the pressure:

$$W = PS_{eddy}^{-1} \quad (5)$$

The change in the thermodynamic potential of the mineral component depends on the eddying generated as a result of interaction between the flow and the surface. The eddying diameter d_{eddy} is assumed to equal 0.3 m in our case. Then, the thermodynamic system potential is expressed as follows:

$$dE = Wnd_{eddy}dt. \quad (6)$$

Figure 2 depicts the hydrodynamic potential E versus the flow rate Q of hydromix with regard to the theoretical formulas (2)–(6). **Figure 3** presents the relationship between the specific particle interphase area S_{ip} ad the flow rate Q from the formula (1).

The hydromix flow rate and the nozzle diameter have influence on the jet velocity, which activates the work energy by interacting with the flat surfaces of the dividers, and by generating the pressure that induces the change in the thermodynamic potential E and the increase in the specific particle interphase area S_{ip}.

It is calculated that after increase in the exposure time by two times and in the hydromix flow rate by five times, in the conditions of the minimal content of the solid phase in the hydromix, the specific interphase area S_{ip}

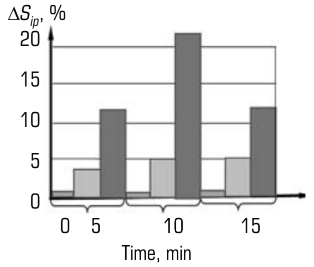

Fig. 4. Change in specific interphase area of particles per time intervals: after soaking, mechanical impact and ultrasonic treatment

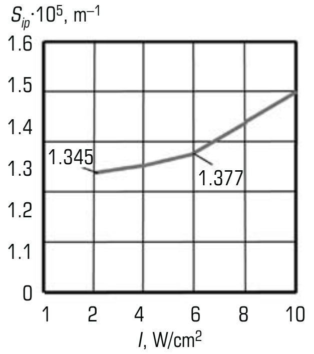

Fig. 5. Specific particle interphase area versus ultrasound radiation intensity I up to 10 W/cm^2 and exposure time of 10 min

of mineral particles grows noticeably. At the exposure time of 2 s, S_{ip} changes from 1.351·10^5 m^{-1} to 1.509·10^5 m^{-1}, and at the exposure time of 4 s, S_{ip} grows from 1.357·10^5 m^{-1} to 1.696·10^5 m^{-1}. At the maximal flow rate and the doubled exposure time, the increase in S_{ip} as compared with the initial value S_{ip0} totals 21%.

At the Placer Mining Laboratory at the Institute of Mining, Far East Branch of the Russian Academy of Sciences, the research was undertaken to study the change in the specific interphase area of clay particles in the hydromix, ΔS_{ip}. The data were obtained using the automated granulometric express-analysis of the disperse phase after soaking, mechanical impact (at the vibration frequency of 80 min^{-1}) and ultrasonic treatment at the emission intensity of 5 W/cm^2 during the time span from 5 to 15 min (**Fig. 4**).

Dispersivity was tested on Laser Particle Sizer Analysette 22. The results proved the low efficiency of change in the specific interphase area of mineral particles in the hydromix after soaking (1–2%), mechanical impact (4–5%) and ultrasonic treatment (12–22%).

Figure 5 shows the plot obtained after ultrasonic treatment of the mineral hydromix at the radiation intensity from 2 to 10 W/cm^2 at the exposure time of 10 min. The plot used the averaged values of the test data.

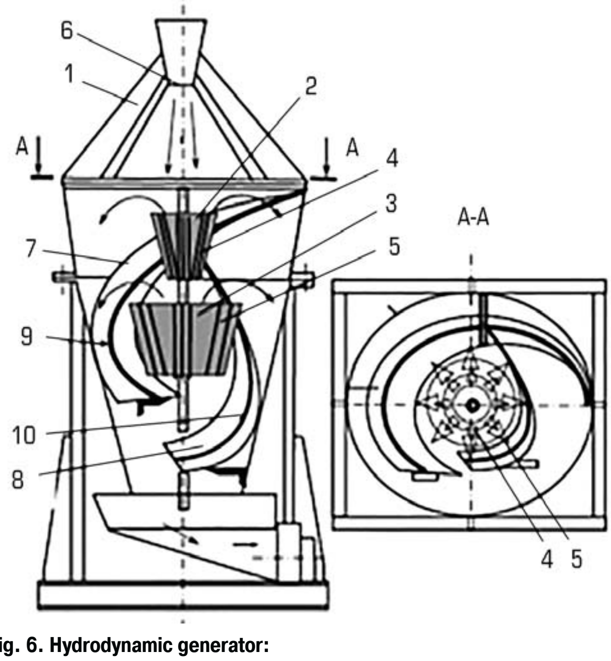

Fig. 6. Hydrodynamic generator:

1–diffusor; 2, 3–cone dividers; 4, 5–blades; 6–nozzle; 7, 8–inclined helix surface; 9, 10–lips

At the maximum intensity of ultrasound radiation of 10 W/cm^2 and at the exposure time of 10 min (see fig. 5), and considering the initial value S_{ip0} = 1.345·10^5 m^{-1} in both cases, the experimental increase in the specific particle interphase area is comparable with the calculated values of S_{ip} in the hydrodynamic effect of the hydromix flow at the minimal flow rate from 1.2 to 6 m^3/h during 2 s. At the time of 4 s, the increase in S_{ip} under the hydrodynamic impact was 11% as against the ultrasonic treatment at the radiation intensity of 10 W/cm^2 within 10 min.

The comparison of the data on hydrodynamic disintegration with the experimental results of the ultrasonic effect on the high-clay component of the hydromix offers grounds for relying on promising nature of modification of hydrodynamic impact facilities using members of flow disintegration—new-type hydrodynamic disintegrators.

Proposed design

The proposed generator design [30] includes the diffusor 1 and the cone dividers 2 and 3 with the blades 4 and 5 (**Fig. 6**). The high-speed jet comes from the nozzle 6 to the cone dividers successively. The cone dividers have the inverse tapers to the jet direction and are set in steps in the center pin of the hydrodynamic generator—along the direction of attack of the hydromix flow in order to divide it and to amplify oscillations.

For activating the processes, the cascade flow of the hydromix is organized; the flow interacts with the inclined helix surfaces 7 and 8 which are shifted along the flow direction and are equipped with the lips 9 and 10 (see fig. 6). The clearance of the cone dividers along the pin is set as function of a solid-to-liquid ratio in the hydromix in order to ensure the assigned average bulk density of the hydrodynamic perturbation and the wanted pressure gradient with the increase of the limit strength of micro particles. Considering the influence of the surface energy of particles, the mineral component of the hydromix undergoes dynamic destruction and breakage of physical and mechanical bond, which means that morphometry and energy of the system also change.

Such transformation phenomenon can actively be used in processing to initiate and intensify physicochemical effects of reagents at their reduced consumption. By aggregative preliminary estimates, the proposed technology with the additional activation of dispersoid formation process provides efficiency 3 times higher than the known technologies of gravity extraction of valuable components.

The proposed method of mineral disintegration in hydromix using hydrodynamic effect in confined environment aims at enhanced technological efficiency, reduced input of energy and improved performance of equipment attendance, at rise in profitability and at higher ecological safety in mineral production. It is urgent to continue research in this field of science.

Conclusions

Based on the modeling of the hydrodynamic microdisintegration of high-clay polymineral component in a hydromix using the proposed new-type hydrodynamic generator, it has been found that the governing part in the energy transformation of the mix flow, with the initiation of the dynamic eddy effect belongs to the time of exposure with regard to the thermodynamic potential of the system, dependent on the bulk flow rate, velocity and pressure of the hydromix jet. At the exposure time increased by two times and at the flow rate increased by 5 times, given the minimum content of the solid phase in the hydromix, the resultant increment in the specific interphase area of mineral particles totaled 21%.

The advanced theoretical and numerical research of hydrodynamics and cavitation effects will make it possible to adjust designs of gravity treatment plants, to improve experimentation accuracy and to engineer adaptable pilot plants suitable for operation at mineral mining facilities. Structural modification of hydrodynamic generators and addition of their designs with stationary destructive members is aimed at energy saving, reduction of losses of valuable mineral fines and at improvement of ecological safety. The application of the energy transformation effect in the mineral preparation processes can promote activation of physicochemical influence of reagents and decrease their consumption. The research in this field of science needs further development.

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References

1. Neronsky G. I., Borodavkin S. I. Method of estimating the contents of gold in placers with dominant small and thin its secretions. *Zolotodobytcha*. 2012. No. 158. pp. 21–24.
2. Kislyakov V. E., Nikitin A. V. Preparation of clay sands of placer deposits for disintegration by controlled water saturation. *Gornyi Zhurnal*. 2010. No. 2. pp. 28–30.
3. Alekseev V. S., Seryy R. S., Sobolev A. A. Improving fine gold recovery in sluice boxes. *Obogashchenie Rud*. 2019. No. 5. pp. 13–18.
4. Khrunina N. P., Mamaev Y. A., Stratechuk O. V., Khrunin T. O. Multilevel plant for recovery of valuable minerals. Patent RF, No. 2187373. Applied: 30.01.2001. Published: 20.08.2002. 2002. Bulletin, No. 23.
5. Khrunina N. P., Mamaev Y. A. Geotechnological complex with multistage disintegration. Patent RF, No. 2209974. Applied: 08.02.2003. Published: 10.08.2003. Bulletin, No. 22.
6. Cheban A. Yu., Shemyakin S. A. Parameters of scrapers for the introduction of layer-strip technologies of open pit mining. *GIAB*. 2007. Vol. 10, No. 12. pp. 285–294.
7. Cheban A.Yu., Shemyakin S.A. Resistance to unloading elongated buckets of scrapers. *Construction and road machines*. 2008. No. 6. pp. 45–48.
8. Ochosov O. Yu., Matveev A. I. Use of centrifugal concentration in by-recovery of gold in diamond-bearing sand processing at Almazy Anabara. *GIAB*. 2021. No. 1. pp. 120–129.
9. Danilov O. S., Belov A. V., Grebenyuk I. V. Ash and slag waste processing with extraction of rare metals as a key factor of social, economic and ecological well-being in coal mining countries. *GIAB*. 2018. No. 7. pp. 16–22.
10. Vanina E. A., Veselova E. M., Leonenko N. A. Mathematical model of the laser agglomeration process based on the distribution of the temperature field in the irradiated sample. *Vestnik Amurskogo gosudarstvennogo universiteta. Series: Natural and Economic Sciences*. 2012. No. 59. pp. 51–54.
11. Khrunina N. P. Improvement of a treatment processes of high-clayey gold-bearing placers. *Eurasian Mining*. 2020. No. 2. pp. 28–32.
12. Michelis I. D, Olivieri A., Ubaldini S., Ferella F., Beolchini F. et al. Roasting and chlorine leaching of gold-bearing refractory concentrate: Experimental and process analysis. *International Journal of Mining Science and Technology*. 2013. No. 23. pp. 709–715.
13. Atici U., Comakli R. Evaluation of the physico-mechanical properties of plutonic rocks based on texture coefficient by. *The Journal of the Southern African Institute of Mining and Metallurgy*. 2019. Vol. 119. pp. 63–69.
14. Sakuhuni G., Altun N. E., Klein B., Tong L. A novel laboratory procedure for predicting continuous centrifugal gravity concentration applications: the gravity release analysis. *International Journal of Mineral Processing*. 2016. Vol. 154. pp. 66–74.
15. De Michelis I., Olivieri A., Ubaldini S., Ferella F., Beolchini F., Vegliò F. Roasting and chlorine leaching of gold-bearing refractory concentrate: experimental and process analysis. *International Journal of Mining Science and Technology*. 2013. Vol. 23. Iss. 5. pp. 709–715.
16. Xun Sun, Songying Chen, Jingting Liu, Shan Zhao, Joon Yong Yoon. Hydrodynamic cavitation: a promising technology for the industrial synthesis of nanomaterials. *Frontiers in Chemistry*. 2020. Vol. 8. DOI: 10.3389/fchem.2020.00259
17. Choi J., Cui M., Lee Y., Ma J., Kim J., et al. Hybrid reactor based on hydrodynamic cavitation, ozonation, and persulfate oxidation for oxalic acid decomposition during rare-earth extraction processes. *Ultrasound. Sonochem*. 2019. Vol. 52. pp. 326–335.
18. Gagol M., Przyjazny A., Boczkaj G. Wastewater treatment by means of advanced oxidation processes based on cavitation — A review. *Chemical Engineering Journal*. 2018. Vol. 338. pp. 599–627.
19. Gagol M. R., Soltani D. C., Przyjazny A., Boczkaj G. Effective degradation of sulfide ions and organic sulfides in cavitation-based advanced oxidation processes (AOPs). *Ultrason. Sonochem*. 2019. Vol. 58. ID. 104610.
20. Kim H., Koo B., Sun X., Yong Yoon J. Investigation of sludge disintegration using rotor–stator type hydrodynamic cavitation reactor. *Separation and Purification Technology*. 2020. Vol. 240. ID. 116636.
21. Fedotkin I. M., Nemchin A. F. The use of cavitation in technological processes. Kiev : Vischa shkola, 1984. 68 p.
22. Balabyshko A. M., Yudaev V. F. Rotor devices with flow modulation and their application in industry. Moscow : Nedra, 1992. 176 p.
23. Chervyakov V. M., Odnolko V. G. Use of hydrodynamic and cavitational phenomena in rotary apparatus. Moscow : Mashinostroenie, 2008. 116 p.
24. Stiles G. F. Cavitation in control valves. *Instruments and Control Systems*. 1961. No. 11. pp. 2087–2097.
25. Sukharkov O. V. Optimization of parameters of direct-flow hydrodynamic emitter in conditions of hydrostatic pressure. *Akusticheskii vestnik*. 2008. Vol. 11, No. 4. pp. 54–63.
26. Dudzinskiy Y. M., Nazarenko A. F. Efficiency of axisymmetric hydrodynamic emitters in conditions of excessive static pressure. *Akusticheskii zhurnal*. 1996. Vol. 42, No. 4. pp. 569–572.
27. Syrotyuk M. G. Acoustic cavitation. Moscow : Nauka, 2008. 271 p.
28. Yakovleva A. A., Maltseva G. D Crystallochemical aspects in the evaluation of clay mineral particle interaction energy. *Proceedings of the Siberian Department of the Section of the Earth Sciences of the Russian Academy of Natural Sciences. Geology, Exploration and Development of Mineral Deposits*. 2018. Vol. 41, No. 1. pp. 99–114.
29. Isaenko I. I., Makhnov A. M., Smirnov E. M., Schmidt A. A. Simulation of high-speed cavitating flows in channels. *St. Petersburg State Polytechnical University Journal. Physics and mathematics*. 2018. Vol. 11, No. 1. pp. 55–65.
30. Khrunina N. P. Method for activating microdesintegration of a polymineral component of a hydraulic slurry. Patent RF, No. 2744059. Applied: 10.09.2020. Published: 02.03.2021. Bulletin, No. 7. EM