UDC 622.7.017:622.765
DOI: 10.15587/1729-4061.2017.118448

HIGH-ENERGY ULTRASOUND TO IMPROVE THE QUALITY OF PURIFYING THE PARTICLES OF IRON ORE IN THE PROCESS OF ITS ENRICHMENT

V. Morkun
Doctor of Technical Sciences, Professor,
Vice-Rector for Research***
E-mail: morkunv@gmail.com
G. Gubin
Doctor of Technical Sciences, Professor, Head of Department
Department of metallurgy of
ferrous metals and foundry production***
E-mail: zagalniy@knu.edu.ua
T. Oliinyk
Doctor of Technical Sciences, Professor, Head of Department*
E-mail: taoliynik@gmail.com
V. Lotous
Chairman of the Board****
E-mail: pgok@ferrexpo.com
V. Ravinskaia
Head of test center****
E-mail: pgok@ferrexpo.com
V. Tron
PhD, Associate Professor**
E-mail: vtron@ukr.net
N. Morkun
Doctor of Technical Sciences,
Associate Professor, Head of Department**
E-mail: nmorkun@gmail.com
M. Oliinyk
PhD, Senior Lecturer*
E-mail: oliinyk.max@gmail.com
*Department of mineral processing and chemistry***
Department of automation, computer science and technology*
***Kryvyi Rih National University
Vitaliya Matusevycha str., 11, Kryvyi Rih, Ukraine, 50027
****PrJSC Poltavskii GOK
Budivelnykiv str., 16, Horishni Plavni, Ukraine, 39800

Погіршення якості концентратів в основному відбувається внаслідок утворення мікронних техногенних зростків. Запропоновано використання високоенергетичного ультразвуку в кавітаційному режимі для очищення поверхонь мінералів. Доведено, що ефективність ультразвукової обробки пов’язана з оновленням поверхонь часток, що призводить до збільшення контрастності магнітних і флотаційних властивостей мінералів. Виконано розрахунок пристрою формування високоенергетичного ультразвуку

Ключові слова: ультразвуковий вплив, очищення мінералів, залізна руда, кавітаційний режим, техногенні зростки

Ухудшение качества концентратов в основном происходит в результате образования микронных техногенных сростков. Предложено использование высокоэнергетического ультразвука в кавитационном режиме для очистки поверхностей минералов. Доказано, что эффективность ультразвуковой обработки связана с обновлением поверхностей частиц, что приводит к увеличению контрастности магнитных и флотационных свойств минералов. Выполнен расчет устройства формирования высокоэнергетического ультразвука

Ключевые слова: ультразвуковое воздействие, очистка минералов, железная руда, кавитационный режим, техногенные сростки

1. Introduction

Iron ore is the main raw material for the metallurgical industry worldwide. The iron ore market largely affects many economies. It is known that today 98 countries of the world have deposits of iron ore of varying quality. Experts estimate that the world reserves of iron ore may be about 790 billion tons. To date, the total reserves of iron ore worldwide are equal to 464 billion tons, of which about 200 billion tons have been already confirmed [1, 2]. Ukraine is one of the leading countries in the world in terms of iron ore reserves, and it has a strong ore mining industry. Significant reserves of iron ore have been discovered on the territory of Ukraine, and their total volume exceeds 32 billion tons. The main volume of ores is concentrated in 52 deposits. Today, mining is carried out in Ukraine in 25 fields: 21 in the Kryvyi Rih basin, 3 in Kremenchuk, and 1 in Bilozerske.

The total volume of extracting commodity iron ore exceeds 1 billion tons per year, with 55–58 % of the raw material being used for smelting metal. Today, iron products are manufactured in 50 countries of the world, with more than 85 % of the output of commodity products being accounted for in 8 countries (Brazil, Australia, China, the USA, India, Canada, Venezuela, and Japan). Ukraine holds the 7th place in the world for producing commodity iron ores (4.9 % of the world output), only behind China, Brazil, Australia, India, the Russian Federation, and the USA [2].

The world reserves of iron ores are mainly of low and medium quality. In part, they account for over 87 percent of the total explored reserves in the world. Such ores contain from 16 to 40 percent of iron and require enrichment. Ukraine is no exception.

The iron-magnetite raw material extracted in Ukraine is characterized by a complex texture, structure, and a high content of harmful impurities such as silicon dioxide, potassium oxides, sodium, magnesium, and sulfur. At the same time, the requirements for the quality of iron ore concentrates entering further metallurgical processing are increasing, as the high quality of magnetite concentrates can significantly reduce the cost of metallurgical production. Magnetite concentrates, which are in demand on the world market, have the following mass fractions: 69–70 % of iron, 2.5–3 % of silicon dioxide, 0.06–0.08 % of sulfur, and about 0.3 % of other harmful impurities [3–5]. The concentration of the raw materials on the world market requires immediate measures to improve the quality of iron ore concentrates and simultaneously reduce their cost at Ukrainian mining and enrichment plants, which can maintain their place on the world market only by improving the production of a concentrate that should contain 69–70 % of iron, not more than 2.5 % of silica, and not more than 0.16 % of K_2O+Na_2O.

Standard solutions in modern conditions do not allow achieving high technical and economic indicators of production. Consequently, new approaches are needed to move to a new technological level of production that provides high-quality indices of world-class iron ore raw materials.

Thus, the need for a deep enrichment of iron ore raw materials to intensify and increase the efficiency of their processing is beyond doubt. Consequently, the important task is to create new and improve existing technologies for producing high-quality iron ore concentrates while reducing the losses of iron with the enrichment waste.

2. Literature review and problem statement

Ores of different types are characterized by mineral composition and texture-structural features, which necessitates the application of various enrichment technologies. In this regard, the depth of enrichment and the technological performance in the processing of ore of each particular type are determined by a number of its characteristics. These characteristics include: the material composition, the nature of the components, the contrast of the properties, and the efficiency of separation processes. The technology of enriching magnetite ores is uniform and involves phased separation with the sequential removal of the nonmetallic part into tails. This is a distinctive feature of the technology of processing magnetite ores, as the enrichment of most minerals is pursued for the purpose of successive removal of disclosed ore minerals into finished products.

Abroad, the improvement of the technology for enriching iron ores is carried out by combining technological schemes. A rough concentrate is obtained according to the schemes of magnetic separation, and then special methods of enrichment are used to improve it. Among the distinguished methods, there are washing, settling, enrichment on concentration tables, extraction by screw separators and heavy suspensions, magnetic enrichment, flotation, and flotogravitation [6, 7].

High-grade concentrates are obtained at the Ukrainian ore mining and enrichment plants with the use of existing magnetic enrichment equipment, and the technology presents some difficulties [7].

The main reasons for this are as follows:

– low separation efficiency due to the redistribution of the material and its increased flocculation;

– insufficient disclosure of minerals with the formation of “heavy” splices;

– clogging of concentrates due to violations of the technological mode (roughness of crushing, breaking of the separators, etc.);

– the predominance of certain types of aggregation of minerals that are unfavorable to the ore opening – poikilitic and myrmekite-like mergers that dramatically reduce the quality of the magnetite concentrate when enriching quartzites;

– the presence in the concentrate of particles the size of which exceeds the standard;

– adhesion of nanosized nonmetallic minerals to magnetite particles that are sent as part of the pulp to magnetic separation;

– flocculation of magnetite particles in the magnetic separator field. In this case, the flocculates include particles of nonmetallic minerals.

It is noteworthy that the quality of concentrates is decreased by re-crushing, which leads to formation of slurry. This is due to the low efficiency of the re-crushing and grading. Thus, if in stage I of the classification in spiral classifiers the efficiency is 50–60 %, then in stage II in hydrocyclones with a diameter of 500–700 mm the efficiency is reduced to 30–38 %. In stage III in hydrocyclones with a diameter of 360–500 mm, the efficiency is reduced to 25–30 %. That is, 70–75 % of the already opened material is again directed with the sands of the hydrocyclone to the last stage of crushing. Therefore, at some plants, the finishing operation consists in using thin screening (for example, at the Kostomukshsky GOK, RF), which allows increasing the mass fraction of iron from 65.7 to 67.6 %. For these purposes, the main screens of thin sifting by Derrick (USA) [8, 9] are used. In order to improve the quality of the concentrate at three ore mining and enrichment plants of Kryvbas (ArcelorMittal Kryvyi Rih, PIVNGZK PJSC, and PIVDGZK PJSC), as well as Poltava GZK, in the period from 2003 to 2015, studies were conducted on the feasibility of using thin screening to improve the quality of the magnetite concentrate. During the experiments, Stack Sizer screens (by Derrick) were used. Research has shown that a high-quality concentrate with a total iron content of more than 67 % can be obtained using the method of thin screening of ordinary concentrate (the mass fraction of total iron in the concentrate at the level of 64.5–65.5 %). It should be noted that the practice of thin screening, as well as the flotation of iron ore concentrates to high quality, has been used at ore enrichment plants in the United States and Canada for many decades.

In Ukraine today, magnetite quartzites are processed with the refinement of concentrates by flotation at the PJSCs Poltava GZK and Inhulets GZK. The flotation of concentrates is the most perfect solution to the problem of removing silica and producing pure magnetite concentrates, even down to the monomine fractions [10], along with the decreasing content of potassium and sodium alkanes, which are part of the rock minerals. The increase in the iron content in the flotation of rolled magnetic concentrates varies at factories from 2 to 9 %. As a result of reverse flotation, it is possible to obtain “superconcentrates” containing more than 70 % of iron and less than 2 % of silica in total. Removal of iron in concentrates depends on the content of magnetite in ores (18–35 %) and varies from 65 to 85 %. The quality of flotation in iron concentrates depends on the mineral composition of ores.

Analysis of works [3–6, 10–11] allows determining the main cause of contamination of concentrates. Its essence lies in the deterioration of the contrast of the technological properties of minerals, which occurs due to magnetic flocculation of particles and the formation of technogenic micron splices. The mechanism of the appearance of technogenic splices is mainly due to the presence of particles of ion-electric and molecular fields on the surface. At first glance, the simplest approach is to apply mechanical fracture of the surfaces of mineral particles, but this does not always lead to the expected results [11]. The formation of technogenic splices reduces the difference in the properties of the surface of the ore and nonmetallic grains, changes their magnetic susceptibility and, consequently, differentiates the efficiency of various separation methods.

A team of researchers at the State Higher Educational Establishment “Krivyi Rih National University” studied the products of enrichment of PJSC TsGZK and PJSC Northern GZK [11]. The specimens were subjected to intense ultrasound. The findings resulted in a conclusion that in different classes of products of magnetic enrichment the mass fraction of iron changed after exposure to ultrasound. In the size classes with the concentration of open grains of minerals (–0.071 mm), the mass fraction of Fe_{tot} increased by 2.7–4.1 %. At the same time, in slurry products (–0.02 mm), it decreased by 14.7 and 7.2 % for the magnetic products of the Ist and Vth stages of enrichment, respectively. This indicates the predominance of cleaning particles from slurry coatings over the release of nonmetallic minerals from magnetic flocculates. Removal of technogenic micron formations occurs both from particles of iron oxides and from particles of quartz and silicates, as a result of which there is a renewal of the surface of particles and an increase in the contrast of technological properties in magnetic separation and flotation.

The study of the processes of purifying the surface of oxidized pyrite in the process of flotation is carried out in work [12]. The performed experiments show that purification of the surface of pyrite with different degrees of oxidation is achieved by ultrasound with an intensity of $\geq$0.3 W/cm^2 for 40 s. It is noted that the effectiveness of ultrasonic influence mainly depends on the length of the material processing. To a lesser extent, the effectiveness depends on the magnitude of the intensity of the ultrasound. In addition, ultrasound contributes to the formation of bubbles, which also increases the effectiveness of flotation.

The method of ultrasonic cleaning of coal with a high content of sulfur in water and mixed alkalis is presented in [13]. The study determined that the effect of ultrasonic fluctuations with a frequency of 20 kHz ensured maximum removal of ash, pyrite sulfur, sulfate sulfur, and total sulfur in the amounts of 87.52 %, 83.92 %, 12.50 %, and 18.80 %, respectively.

The influence of ultrasonic cavitation on the purification of particles in liquids was investigated in work [14]. It is noted that ultrasonic cavitation in a liquid medium causes a number of physical and chemical effects. Fluctuations and collapse of cavitation bubbles moving at low ultrasound frequencies (20 kHz) can generate strong shear forces, microcurrents, and shock waves. It is indicated that these effects can be used to influence the surface activity of solid particles in a liquid.

It is stated in paper [15] that a powerful ultrasound can be used to enrich coal for the removal of sulfur from it. It is noted that the main effects of ultrasound in a liquid medium are acoustic cavitation and acoustic currents. It has been proven that application of ultrasonic influence helps achieve better purification in comparison with chemical methods.

The tests on the laws of cavitation processes in the pulp [16] resulted in forming a method for determining the optimal parameters of ultrasonic vibrations to maintain the cavitation mode. The proposed analytical dependence allows calculating the values of the optimal frequency, taking into account a certain size of gas bubbles in the pulp.

Consequently, an increase in the quality of magnetite concentrates is possible due to removing and destroying the so-called technogenic splices from the surface of minerals of clayey sludge particles. The analysis of the main directions and approaches in this issue has shown that the application of high-energy ultrasound of a certain intensity for the pretreatment of the iron ore pulp before flotation will form a clean surface of mineral particles. Thus, due to the disintegration of ore flocculoforms, the output of the high-quality concentrate will increase. Therefore, improvement of the technology of flotation of magnetite concentrates is proposed due to the use of a pulsed magnetic field of decreasing tension and high-energy ultrasound in the cavitation mode.

3. The aim and objectives of the study

The aim of the work is to improve the quality of cleaning iron ore particles in the process of the ore enrichment with the use of high-energy ultrasound to increase the efficiency of the technology of flotation enhancement of magnetite concentrates.

To achieve this aim, the following research tasks were solved:

– to perform simulation, to investigate the influence of the dynamic effects of ultrasonic vibrations on the ore pulp in the process of enrichment, and to determine the optimal parameters of the source of ultrasonic vibrations to provide the necessary intensity and direction;

– to investigate the possibility of using pretreatment of the iron ore pulp with the help of high-energy ultrasound to improve the purification efficiency;

– to determine the optimum values of the intensity and duration of ultrasonic treatment in the purification of mineral particles;

– to investigate the effectiveness of ultrasonic influence on the reduction of the mass fraction of nonmetallic oxides in purified samples of flotation probe samples.

4. Materials and methods for studying ultrasonic influence on the parameters of magnetic flotation enrichment

4. 1. Materials and equipment used in the experiment

The research work included a complex of methods such as generalization of scientific information; X-ray and mineral analysis of ore and enrichment products; research on the methods of forming high-energy ultrasound. The study also included simulation and analysis of high-energy ultrasound effects; technological tests in laboratory conditions; synthesis of analytical regularities; and substantiation of rational parameters of the process of flotation finishing of magnetite concentrates. Experimental tests were carried out using a specially designed laboratory complex, which included the following equipment: an ultrasonic disperser with a regulated intensity and power of 130 W, an emitter with a mushroom working end with a diameter of 18 mm and a radiation area of 254 mm^2, microscopes Nu and Vertival and a precision microscope, a stopwatch, and a thermometer. The investigated disperse media used in experiments were samples of very finely dissolved magnetite quartzites. Sampling was carried out at the testing of the ecological scheme of enrichment in the conditions of PJSC Poltava GZK: the powering and unloading of a vertical mill, a magnetic separation feed, as well as the concentrates and flotation waste of magnetic products.

4. 2. Methods of research on ultrasonic processing of products

To simulate the process of spreading the ultrasonic signal in a fluid medium, under conditions of change in the velocity of sound propagation and density change, the study involved the use of the k-space method of the first and second orders, based on the system of linear equations of the first order [17].

Experimental tests of the products were carried out according to the scheme below (Fig. 1). The imposition of product samples was subjected to ultrasound treatment, and further, washing of each treated sample in a weak magnetic field was carried out. To equalize the results in a weak magnetic field, a sample of the product that had not been subjected to ultrasound was washed. Further, optical mineralogical research of the products was conducted.

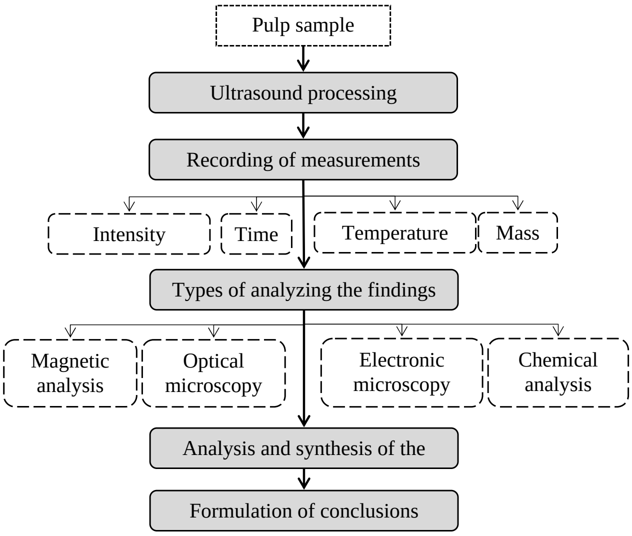

Fig. 1. A general scheme of research on the ultrasonic processing of pulp samples

Acoustic power was measured to assess the degree of temperature rise $\Delta T = T_2 - T_1$ of the liquid medium in the volume V during the time of the ultrasound effect on the liquid (t), with the known heat capacity C and density ρ, using the following formula:

$$P = \frac{C\rho V \Delta T}{t}. \tag{1}$$

Since practically all acoustic energy is converted to heat, the measurement of the final temperature t_2 allows using the calculated formula to calculate the acoustic power.

Using the capabilities of a scanning microscope, it is possible to determine the presence or absence of adhesive contamination with rock particles on the surface of the exposed ore grains. With the help of spectroscopy and software, it is possible to determine the mineral composition of contaminants, the size of nonmetallic inclusions, etc. All images of the raster electronic microscope are made in shades of gray. For the visualization effect, such images are not suitable, since when the size of the particles under study is reduced, the contrast of the images increases. In some cases, the images of ore and rocky grains look the same, and they can be distinguished only by the results of spectroscopy. Therefore, in the tests, the priority indicators of the degree of purification were the chemical analysis of the processed products and enrichment tests using a Davis tube.

5. Results of simulating the influence of ultrasonic signal in the medium

The mathematical description of cavitation processes in a heterogeneous environment adapted to the flotation process of iron ore enrichment is discussed in detail in [16].

To create a model of the effect of high-energy ultrasound on the pulp flow, it is necessary to calculate the device for the formation of high-energy ultrasound with controlled parameters.

For a two-dimensional medium without loss, the equations of the ultrasonic signal propagation in a fluid medium under conditions of change in the velocity of the sound propagation and the density change have the following form [17, 18]:

$$\rho(r)\frac{\partial u(r,t)}{\partial t} = -\nabla p(r,t),$$

$$\frac{1}{\rho(r)c(r)^2}\frac{\partial p(r,t)}{\partial t} = -\nabla u(r,t), \tag{2}$$

where u is the velocity vector of the ultrasonic particle with components u_x and u_y, p is the ultrasonic pressure fluctuations, $\rho(r)$ is the density of the medium, $c(r)$ is the sound velocity in the medium, and r is the coordinate vector (x, y).

The second-order wave equation corresponding to expression (2) has the following form [17, 18]:

$$\nabla\left(\frac{1}{\rho(r)}\nabla p(r,t)\right) - \frac{1}{\rho(r)c(r)^2}\frac{\partial^2 p(r,t)}{\partial t^2} = 0. \tag{3}$$

Let us consider the procedure for numerical solution of the above equations by the k-space method. To simplify considerations, we believe that the velocity of sound and density are constant, that is, $\rho(r) = r_0$, and $c(r) = c_0$. The general principles that underlie the k-space method are given in [19]. At the same time, the method under consideration can be extended to the case of a heterogeneous medium.

For narrowband signals, such as ultrasonic pulses, very accurate spatial derivatives can be obtained by the Fourier transform of the pressure field [20].

This principle is at the core of the pseudospectral methods described in particular in [21]. Spatial derivatives of equation (2) are calculated using the discrete Fourier transform and time iteration, which are implemented using the Adams-Bashforth and Adams-Moulton methods of the fourth order. For a case of a uniform velocity of sound and density, equation (3) can be written in the space-frequency domain in the following way:

$$\frac{\partial^2 \hat{p}(k,t)}{\partial t^2} = -c_0^2 k^2 \hat{p}(k,t), \tag{4}$$

where $\hat{p}(k,t)$ is a two-dimensional spatial Fourier transform of the ultrasonic pressure fluctuations $p(r,t)$.

The discrete representation of the left-hand side of equation (3) is obtained using the second-order finite difference method. Consequently, the approximate pseudo-spectral method is described by the expression

$$\frac{p(r,t+\Delta t) - 2p(r,t) + p(r,t-\Delta t)}{(\Delta t)^2} = \\ = c_0^2 F^{-1}\left(k^2 F\left(p(r,t)\right)\right), \tag{5}$$

where F is the operator of a two-dimensional Fourier transform of space. In numerous realizations of equation (4), the spatial derivatives from the right-hand side of equation (3) are precisely represented using a discrete Fourier transform.

The considered pseudo-spectral methods [17, 20, 21], as a rule, use approaches of time integration of a higher order to reduce disorientation errors. However, for a homogeneous medium, the time iteration can be performed precisely, that is, without any dispersion using the *k–t* method of space [19]:

$$\frac{\hat{p}(k,t+\Delta t) - 2\hat{p}(k,t) + \hat{p}(k,t-\Delta t)}{(\Delta t)^2 \sin(c_0 \Delta t k/2)^2 / (c_0 \Delta t k/2)^2} = \\ = -(c_0 k)^2 \hat{p}(k,t). \tag{6}$$

The method of time iteration is mathematically equivalent to the method originally presented in [17].

As shown in [19], the time accuracy of this method follows from the exact discrete representation of the differential equation of the harmonic oscillator described in [22]. The time iteration can be performed in the spatial-frequency domain, as shown in [19], using the generalized form of equation (5). Also, an equivalent iterative method can be obtained by using the inverse spatial Fourier transform of equation (5). The resulting iterative formula has the form [17]:

$$\frac{p(r,t+\Delta t) - 2p(r,t) + p(r,t-\Delta t)}{(\Delta t)^2} = \\ = c_0^2 F^{-1}\left(k^2 \frac{\sin(c_0 \Delta t\ k/2)}{c_0 \Delta t\ k/2} F\left(p(r,t)\right)\right). \tag{7}$$

To the right-hand side of equation (6), we apply the k-space operator of the second order, which looks as follows:

$$\left(\nabla^{(c_0\Delta t)}\right)^2 p(r,t) \equiv \\ \equiv -F^{-1}\left(k^2 \frac{\sin(c_0 \Delta t\ k/2)^2}{(c_0 \Delta t\ k/2)^2} F\left(p(r,t)\right)\right), \tag{8}$$

where $(c_0 \Delta t)$ is the upper index that indicates that the operators used are the standard gradient operator and also the functions of the parameter $(c_0 \Delta t)$.

The form of equation (6) implies that the method of k-space of the second order can be considered as a modified finite difference method, in which the spatial Laplacian is replaced by the k-space operator. However, the k-space operator in equation (7) includes not only the spectral estimation of the Laplacian but also the time correction element associated with the k-t spatial iterator of equation (5).

To apply the k-space method to a system of first-order equations describing wave propagation, the k-space operator of the second order can be used. For this, the operator of the second order is divided into parts that are associated with each spatial direction. For a two-dimensional case, this procedure is performed in the following way:

$$\frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^+} x} \equiv F^{-1}\left(i k_x e^{i k_x \Delta_x/2} \frac{\sin(c_0 \Delta t\ k/2)}{c_0 \Delta t\ k/2} F\left(p(r,t)\right)\right);$$

$$\frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^+} y} \equiv F^{-1}\left(i k_y e^{i k_y \Delta_y/2} \frac{\sin(c_0 \Delta t\ k/2)}{c_0 \Delta t\ k/2} F\left(p(r,t)\right)\right);$$

$$\frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^-} x} \equiv F^{-1}\left(i k_x e^{i k_x \Delta_x/2} \frac{\sin(c_0 \Delta t\ k/2)}{c_0 \Delta t\ k/2} F\left(p(r,t)\right)\right);$$

$$\frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^-} y} \equiv F^{-1}\left(i k_y e^{i k_y \Delta_y/2} \frac{\sin(c_0 \Delta t\ k/2)}{c_0 \Delta t\ k/2} F\left(p(r,t)\right)\right), \tag{9}$$

so that

$$\left(\frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^+} x}\frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^-} x} + \frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^+} y}\frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^-} y}\right) p(r,t) = \\ = \left(\nabla^{(c_0\Delta t)}\right)^2 p(r,t). \tag{10}$$

The spatial-frequency components k_x and k_y are defined so that $k^2 = k_x^2 + k_y^2$.

Using the operators of equation (8) in equation (2) makes it possible to form the *k*-space method of the first order as equivalent to (6). The application of the exponential coefficients from equation (8) requires the estimation of the velocities of the ultrasonic wave of u_x and u_y in the points of the array at the intervals $\Delta x/2$ and $\Delta y/2$, respectively. The resulting algorithm has the form

$$\frac{u_x(r_1,t^+) - u_x(r_1,t^-)}{\Delta t} = \frac{1}{\rho(r_1)} \frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^+} x};$$

$$\frac{u_y(r_2,t^+) - u_y(r_2,t^-)}{\Delta t} = \frac{1}{\rho(r_2)} \frac{\partial p(r,t)}{\partial^{(c_0\Delta t)^+} y};$$

$$\frac{p(r,t+\Delta t) - p(r,t)}{\Delta t} = \\ = -\rho(r) c(r)^2 \left(\frac{\partial u_x(r_1,t^+)}{\partial^{(c_0\Delta t)^-} x} + \frac{\partial u_y(r_2,t^+)}{\partial^{(c_0\Delta t)^-} y}\right), \tag{11}$$

where

$$r_1 \equiv (x + \Delta x/2, y),\ r_2 \equiv (x, y + \Delta y/2),$$

$$t^{+} \equiv t + \Delta t / 2, \quad t^{-} \equiv t - \Delta t / 2. \qquad (12)$$

In equation (11), the spatially varying values of the sound speed and density $c(r)$ and $r(r)$ are used instead of the coefficients c_0 and ρ_0. The spatial distribution in equation (10) is implicitly included in the spatial derivatives of the considered operators. For example, the operators $\partial / \partial^{(c_0 \Delta t)^{+}} x$ and $\partial / \partial^{(c_0 \Delta t)^{-}} x$, which are defined by formula (9), correspond to the derivatives calculated after the spatial shifts of $\Delta x / 2$ and $-\Delta x / 2$, respectively.

The nature of the change in the concentration of particles and their distribution by size in the field of high-energy ultrasound depends on the density of the particles themselves, the frequency and intensity of the radiation. Let us evaluate the effect of radiation pressure of ultrasound on the change in the concentration of particles of the radius r. Let us suppose that in the positive direction of the x axis, a pulse flows at a velocity V. We denote by $n_r(Z, t)$ the concentration of particles of the radius r at the depth Z at the time t. In view of the aforementioned, it is possible to write down that

$$\frac{\partial n_r(Z,t)}{\partial t} = -\frac{\partial}{\partial Z}\left[V_r(Z,t) n_r(Z,t)\right]. \qquad (13)$$

In this equation, $V_r(Z, t)$ is the rate of displacement of a particle of the radius r with the coordinate Z in the ultrasonic field. The velocity is directed along the z axis, that is, it is perpendicular to the flow of the pulp. In general, it depends on the time t, as the concentration of particles changes as a result of ultrasound, which results in a change in the intensity of the ultrasound, which ultimately affects the particle shift rate. However, this greatly complicates the solution of equation (12), so we will assume that the speed depends only on the coordinate Z.

Assuming that the intensity of the ultrasonic wave I varies according to the exponential law (initial value), the coefficient of its attenuation α depends on the frequency of the sound ν_o and, taking into account the analysis performed in [23], the concentration of the particles $n_r(Z, t)$ is determined by the formula

$$n_r(Z,t) = n_0 \frac{e^{\alpha z}}{e^{\alpha z} - \alpha\beta t} St(e^{\alpha z} - 1 - \alpha\beta t), \qquad (14)$$

where $n_r(Z,0) = n_0$, $n_r(0,t) = 0$ are the initial and final conditions;

$$St(X) = \begin{cases} 0, & X < 0; \\ 1, & X \geq 0; \end{cases}$$

$$\beta = \frac{2r(kr)^4}{27\eta c} I_0 \left(a_1^2 + a_1 a_2 + \frac{3}{4} a_2^2 \right)$$

and

$$a_1 = 1 - \frac{\mathrm{r c}^2}{\rho\ \mathrm{c}^2}; \ a_2 = 2\frac{\rho - \rho}{2\rho + \rho};$$

ρ_{T} and c_{T} are the particle density and ultrasound velocity in the particle material; ρ and c are the density of the investigated medium and the speed of the ultrasound in it.

When increasing the intensity of high-energy ultrasound from zero to a certain value and the constant velocity of the pulp flow in the measuring zone, all or only individual size classes of the crushed material can be shifted [23]:

$$F(r) = \frac{\left(\int_0^{r_1} f(r) r^3 \mathrm{d}r + \int_{r_1}^{r_2} f(r) r^3 \mathrm{d}r + \ldots + \int_{r_{m-1}}^{r_m} f(r) r^3 \mathrm{d}r \right)}{\int_0^{r_m} f(r) r^3 \mathrm{d}r}. \qquad (15)$$

The power of high-energy ultrasound, which makes it possible to predict displacement of particles of crushed ore of a certain mass in the pulp flow, was calculated using the package HIFU Simulator v1.2 [24].

Thus, the simulation and analysis of the dynamic effects of high-energy ultrasound on the ore pulp have helped develop a method for changing the trajectory of the motion of particles of a certain size class.

Article [25] considers forced fluctuations of monopole domain margins under the action of ultrasonic waves propagating along them. This phenomenon is explained by the fact that ultrasound causes variable mechanical stresses in particles of iron, which leads to an increase in the magnitude of the magnetoelastic energy U_d, which is generally determined from the expression [26]

$$U_d = -\sigma \cdot \lambda, \qquad (16)$$

where λ is magnetostriction, and σ is stress. In accordance with the law of anisotropy by M.S. Akulov, the expression for U_d takes the following form:

$$U_d = -\sigma \cdot \left(a_1 \sum_{i=1,2,3} \left(S_i^2 \beta_i^2 - \frac{1}{3} \right) + a_2 \sum_{i \neq j} \left(S_i S_j \beta_i \beta_j \right) \right). \qquad (17)$$

To preserve the condition,

$$\frac{\partial \left(U_k + U_d + U_m \right)}{\partial \alpha} = 0, \qquad (18)$$

where U_k is the energy of the magnetic anisotropy of the crystal; U_n is the energy of the external magnetic field.

According to expressions (15)–(18), if the energy of U_n changes, then the magnetization of the particles will increase.

Below, the design of the channel of influence of high-energy ultrasonic oscillations on the pulp flow performed by ultrasonic phased array technology is considered.

The ultrasound phase array is viewed as a set of point sources of ultrasound, located at the same distance (d) from one another. The design is developed on the basis of studying the influence of the distance between elements, the wavelength and the number of elements on the controllability and efficiency of ultrasonic radiation [23].

The pressure of the ultrasonic field is determined using the Huygens principle according to the formula [27]

$$p(r,\theta,t) = \frac{p_0 r_0}{r} \frac{\sin(\chi N)}{\sin(\chi)} e^{-j\chi(N-1)} e^{j(\omega t - kr)},$$

$$\chi = \frac{\omega \Delta\tau - kd \sin\theta}{2}, \qquad (19)$$

where r_0 is the infinitely small radius of the pulsed point sources of ultrasound radiation; p_0 is the amplitude of pressure of the point sources of ultrasonic radiation; k is the wave number; ω is the angular frequency; *N* is the number of point sources of ultrasound radiation; and *j* is the imaginary unit. The required delay time between neighboring sources is determined by the direction of ultrasound radiation at an angle θ_s and is given by the ratio [28]

$$\Delta\tau = \frac{d\sin\theta_s}{c}, \tag{20}$$

where *c* is the speed of sound in the medium of propagation (the reference liquid, water, and the iron ore pulp, respectively).

The direction of ultrasonic radiation, based on expression (8), will then be determined as

$$H(\theta) = \left| \frac{\sin\left(\frac{\pi d(\sin\theta_s - \sin\theta)}{\lambda}\right)}{N\sin\left(\frac{\pi d(\sin\theta_s - \sin\theta)}{\lambda}\right)} \right|. \tag{21}$$

The optimal parameters of the ultrasonic phase array are selected on the basis of the indicators characterizing the direction diagram of the ultrasonic phase array (Fig. 2).

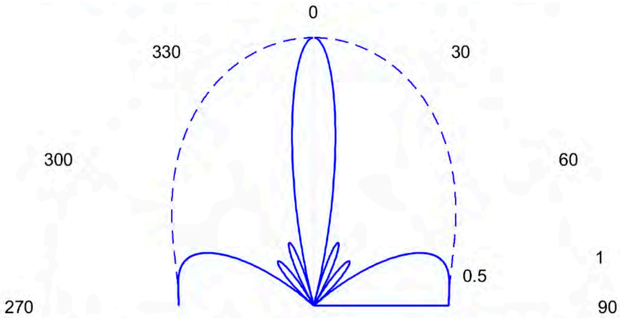

Fig. 2. A diagram of the direction of the ultrasonic phased array: —— total; ------ – of a point element

The index of the width (sharpening) of the main petal of the diagram, taking into account (20), is determined by the formula

$$q = \frac{1}{\pi}\left(\sin^{-1}\left(\sin\theta_s + \frac{\lambda}{Nd}\right) - \sin^{-1}\left(\sin\theta_s - \frac{\lambda}{Nd}\right)\right). \tag{22}$$

In this case, the better orientation corresponds to less than the value of the *q* index. It should be noted that in the case when the value of λ/Nd is close to zero, then *q* also goes to zero. Thus, a better orientation can be achieved by applying a greater number of radiating point elements or by increasing the distance between these elements.

Based on expression (22), which describes the width of the main petal of the directional diagram, we can conclude that the increase in the number of elements of the ultrasonic phase array raises efficiency. However, the results of study [27] show that the value of the index *q* sharply decreases when the number of piezoelements in the phase array varies up to 8. If the number of elements exceeds 32, an increase in their number does not bring a significant improvement in the index *q*. Taking into account this circumstance, the optimal number of elements in terms of improving the direction of the phased array and the cost of its manufacturing is 16 [23, 27].

The distance between the elements is also an essential indicator that affects the radiation pattern of the ultrasonic phased array. In [27], it is shown that a greater distance between elements of a phased array corresponds to a better value of the direction indicator. However, it should be noted that, along with the change in the direction of *q*, the lateral petals of the directional diagram also increase. This is confirmed in Fig. 9 by the results of calculating the directional patterns of the ultrasonic phased array with 16 elements (4×4) with a change in the distance between the elements from 0.4 mm to 0.7 mm in increments of 0.1 mm.

Consequently, it is necessary to find a compromise value of the distance between the elements of the phased array. This value, on the one hand, provides the optimal level of the radiation direction, and on the other hand, it provides reduction of the side petals of the directional diagram. From equation (20) under condition $H(\pi/2)=1$, the distance between the elements of a phased array is determined as follows

$$d_{cr} = \frac{1}{1+\sin\theta_s}. \tag{22}$$

As a result of simulation and calculation, the obtained optimal value of the distance between the elements of the ultrasonic phased array is equal to d_{cr}=0.45 mm.

The three-dimensional representation of the directivity diagram of this ultrasonic phased array is shown in Fig. 3.

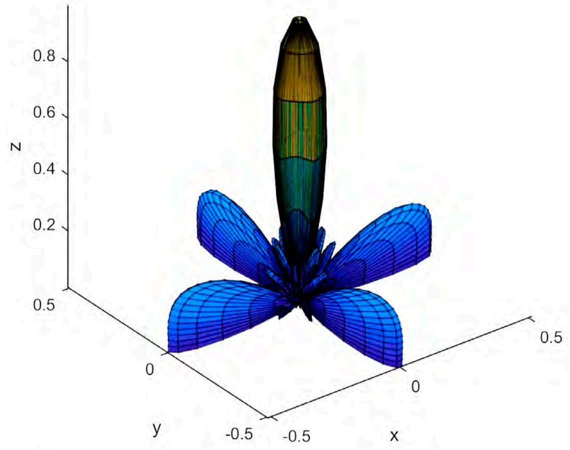

Fig. 3. A diagram of the orientation of the ultrasonic phase array at a distance between the elements d_{cr}=0.45 mm

Thus, a pretreatment of the iron ore pulp with the help of high-energy ultrasound is a promising direction of increasing the efficiency of the process of flotation of the iron ore concentrate by purifying the particles of the useful component from the sludge. This approach can prove that the effectiveness of ultrasonic treatment is associated with the renewal of particles surfaces, which leads to an increase in the contrast of the magnetic and flotation properties of minerals.

6. Discussion of the results of studying the ultrasound influence on the indicators of magnetic flotation enrichment

To confirm the simulation results, samples of products from technological flows of magnetic flotation enrichment of fine and very finely dispersed magnetite quartzites of the Kremenchuk iron ore district were selected. The samples were processed using a pulsed magnetic field of decreasing tension and high-energy ultrasound in a cavitation mode modulated by high-frequency pulses. Grinding in a vertical mill reveals splices of nonmetallic minerals with magnetite in the form of particles of various sizes. The material for unloading the mill is characterized by high content of nonmetallic minerals: quartz – 12.5 %, cummingtonite – 5.3 %, carbonate – 4.9 %, aegirine and riebeckite – 2 %, and iron hydroxides – 2.2 %. Non-ore minerals are represented by microdisperse minerals. Their content in the material is 24–26 %. The density of these nonmetallic minerals in comparison with magnetite or hematite is 1.5–2 times less. That is, the product of unloading the mill is a mixture of mineral ore and nonmetallic grains with a bulk ratio of ~ 2:1. Such a product is complicated by the size and the ratio of the ore and nonmetallic minerals to separation processes in magnetic fields and requires the application of many stages of enrichment.

The mineralogical analysis has shown that the surface of mineral particles in unloading the mill is the least contaminated with slag in comparison with other products. However, in a laboratory experimental installation, the separation of a product without prior ultrasound treatment did not significantly improve the quality of the material: the mass fraction of Fe_{tot} in the purified product had increased by 0.41 %. Then, after ultrasonic treatment for 60 s and at an impact intensity of 1.62 W/cm^2, the quality of the purified product increased by an additional 0.4–0.5 % while the magnetite extraction increased by 1.1 %. The ultrasonic effect created favorable conditions for the separation of even relatively “pure” fine particles across the contaminated surface. Simultaneously with the improvement of the quality of the purified product, its yield increased due to the selective magnetic flocculation of the fine magnetite particles purified from the nonmetallic sludge. The effectiveness of cleaning the product, namely the discharge of a vertical mill from nonmetallic minerals, was calculated by using the Hancock-Luiken criterion: it increased by 2.2–2.5 % or 1.8–2.1 times in the application of ultrasonic treatment.

Subsequently, the influence of the intensity of the ultrasonic influence on the parameters of cleaning the mineral surface from the slurry particles was studied.

The ultrasonic treatment of the material at an impact intensity of 1.6 W/cm^2 and duration of up to 60 s has helped obtain a dispersed material with a small amount of slurry coatings of mineral grains. With an increase in the intensity of ultrasound exposure up to 2.2–2.95 W/cm^2, the cleaning performance of products is sharply reduced. Ultrasonic treatment allows clearing the surface of the ore particles from all sorts of mineral coatings. In [11], the possibility of ultrasonic purification of minerals from iron oxides was shown. The physical basis for applying ultrasound is its dispersant effect on the dispersion medium [29]. However, ultrasound treatment, especially in liquid vs. solid systems, can also lead to coagulation of particles and their adhesion (coalescence) [30]. The initial stage of this process is the convergence of particles of the dispersed phase and their mutual fixation at small distances from one another. Between the particles, there remain layers of the medium: double electric layers and hydrated shells of particles. Long and intense ultrasonic effects on the pulp can lead not only to the cavitation dispersion of fine particles but also to changes in properties of both the liquid phase and the surfaces of solid grains. Therefore, with ultrasonic influence on the pulp, there should be an optimal dispersion mode based on the intensity of the ultrasonic wave pulse and the duration of the process.

Saturation of the pulp by cavitational steam-gas bubbles increases its wave resistance. The increase of the wave resistance of the liquid medium leads to an increase in the output of acoustic energy in it, that is, it increases the active losses associated with the radiation of ultrasonic energy in the medium. The steam-gas bubbles absorb the energy of the ultrasonic waves and shield the solid particles from their effects. Acoustic power, which is introduced into the environment, increases, and the effectiveness of its effect on solid particles is reduced.

High values of ultrasonic influences change the kinematics of the oscillatory motion of mineral parts, increasing the probability of their collision with one another and gas bubbles. There is a decrease in the surface energy of particles and coagulation. The results of experiments have shown that at high intensity of ultrasonic influence or with prolonged influence on the pulp, the yield of the purified product increases. This is due to an increase in the content of its nonmetallic and ore minerals, and its quality is reduced. For example, with an increase in ultrasound treatment from 60 seconds to 240 seconds, the amount of pulsed ultrasound power increased from 3.5 W to 11.5–12 W, and the quality of the product being purified is reduced. There is a dissipation of ultrasonic energy in the liquid phase of the pulp, which causes a sharp decrease in the processing efficiency.

The analysis of the results of ultrasound processing of the supply load for reverse flotation of magnetite has shown the following. With the increase in the intensity of ultrasonic influence, the quality of the washed product rises by 0.3–0.48 % to reaching the maximum. With further increase in intensity, the qualitative indicators are reduced slightly, unlike in the previous experiment, where there was a sharp decline in quality. This is due to the fact that the product is characterized by a significantly lower content of large nonmetallic grains. The output of the product after ultrasound processing increases with an intensity of 1.2–1.9 W/cm^2 and a processing time of 60–120 seconds. At a higher processing speed, the output decreases. The processing time of 240 seconds leads to a decrease in the yield of the washed product throughout the range of the impact intensity. The optimal treatment parameters for the Fe_{tot} extraction index in the washed product during the purification of mineral particles are the intensity of 1.2 W/cm^2 and the processing time of no more than 60 seconds. In this case, the yield of the purified product is increased by 0.8 % and its quality grows by 0.9 %. The efficiency of washing under the Hancock-Luiken criterion increases with the use of ultrasound treatment from 1.7 % to 3.1 %, i.e. 1.8 times.

To evaluate the losses of the ore mineral with waste and the degree of clogging of the flotation concentrate by nonmetallic fine particles, ultrasonic analysis of concentrate and flotation waste was carried out. After the ultrasound processing, the quality of the flotation concentrate was practically unchanged, and with a long process, it even slightly decreased. This is due to the fact that all mineral grains were intensively cleared during the process of ultrasonic treatment, but falling into the weak magnetic field of the experimental plant in the liquid phase, these grains form magnetic flocculates, which include poor iron-containing silicates. In this case, the quality of the final concentrate does not grow, but the yield increases.

The analysis of the results of purifying the flotation waste of magnetite concentrates has shown that the ultrasonic effect cleans the surface of minerals from the sludge particles and disperses the whole solid phase. This creates favorable conditions for removal of nonmetallic minerals under experimental conditions. The output of the washed product (waste) is reduced by 1.8–2 %, and with an increase in the intensity of exposure to more than 1.62 W/cm^2, it increases. The mass fraction of iron in this product is reduced by 2.2–2.3 % while the purification efficiency rises 1.4 times.

The ultrasonic effect also reduces the mass fraction of nonmetallic oxides in the refined products of the flotation test samples. In the range of the intensity of ultrasound influence from 1.2 to 2.2 W/cm^2, there is a significant decrease in the concentration of oxides in the purified product. The concentration of the oxides K_2O, Na_2O, MgO, and Al_2O_3 in the purified product is reduced 1.2 to 3 times. A further increase in intensity leads to a decrease in the ultrasound effectiveness.

In the future, high-energy ultrasound can be used to increase the efficiency of the main technological processes of enrichment production. In the process of enrichment, as shown by studies [31, 32], it is necessary to take into account the distribution of physical and mineralogical characteristics of ore in terms of grain size classes. These characteristics of ore raw materials become particularly important in the process of flotation [33, 34]. The justification for the need to select the technological parameters of the flotation process in accordance with the distribution of the size of the ore particles is proposed in [33]. In work [34], the influence of chemical characteristics of ore particles on the efficiency of the flotation process is investigated. Studies show that the presence of this information is important in optimizing the parameters of the ore enrichment process [35–37], the formation of mathematical models [38, 39], and the synthesis of controlling the enrichment process [40–42]. The application of high-energy ultrasound, as shown in this article, allows for a controlled shift of particles of a certain size into the area of measurement. Consequently, it becomes possible to determine the distribution of certain physical, mechanical, chemical and mineralogical characteristics by the size classes of ore particles.

7. Conclusions

Standard solutions in modern conditions do not allow achieving high technical and economic rates of production. Consequently, in order to move to a new technological level of manufacturing and achieve high-quality indices of iron ore raw materials worldwide, the performed research has resulted in the following findings.

1. The results of simulating and analyzing the dynamic effects of ultrasonic vibrations on the ore pulp have revealed the optimal value of the distance between the elements of the phased array as the source of ultrasonic oscillations. This value (d_{cr}=0.45 mm) provides the optimal radiation direction and, on the other hand, helps reduce the side petals of the directional diagram.

2. It has been determined that the use of pretreatment of iron ore slurry with the help of high-energy ultrasound can improve the efficiency of cleaning ore raw materials. In particular, the efficiency of cleaning nonmetallic minerals from the vertical mill by using the Hancock-Luiken criterion was increased by 2.2–2.5 %.

3. The optimal parameters of treatment according to the index of iron extraction in the purified product have been determined. When cleaning mineral particles, the intensity should be 1.2 W/cm^2; the processing time should not exceed 60 seconds. In this case, the yield of the purified product is increased by 0.8 %, and its quality grows by 0.9 %. The cleaning efficiency by the Hancock-Luiken index rises from 1.7 % to 3.1 %.

4. It has been established that ultrasonic influence also reduces the mass fraction of nonmetallic oxides in purified products of flotation finishing. In the interval of the intensity of ultrasound influence from 1.2 to 2.2 W/cm^2, the concentration of the oxides K_2O, Na_2O, MgO, and Al_2O_3 in the purified product significantly decreases 1.2–3 times. At the same time, a further increase in intensity leads to a decrease in the effectiveness of ultrasound.

References

1. Matyuha, V. V. Sovremennoe sostoyanie mineral'no-syr'evoy bazy chernoy metallurgii Ukrainy [Text] / V. V. Matyuha, N. T. Movchan // Gorniy zhurnal. – 2011. – Issue 4. – P. 65–67.
2. Bol'shakov, V. I. Gorno-metallurgicheskiy kompleks Ukrainy (tsifry, fakty, kommentarii). Biznes-spravochnik [Text] / V. I. Bol'shakov, S. P. Vasilenko, L. S. Galetskiy et. al.; V. A. Gnatush (Ed.). – Kyiv, 2009. – 732 p. – Available at: http://cgntb.dp.ua/pn_book.html
3. Sentemova, V. A. Flotatsiya v skhemah obogashcheniya magnetitovyh rud [Text] / V. A. Sentemova // Obogashchenie rud. – 2007. – Issue 2. – P. 18–22.
4. Oliinyk, T. A. Rozrobka tekhnolohiy ochyshchennia zalizovmisnykh kontsentrativ vid shkidlyvykh domishok [Text] / T. A. Oliinyk, E. V. Chasova, L. V. Skliar, N. V. Kushniruk, M. O. Oliinyk, A. Yu. Skliar // Zbahachennia korysnykh kopalyn. – 2016. – Issue 62 (103). – P. 34–44.
5. Goncharov, S. A. Povyshenie effektivnosti obogatitel'nyh tekhnologiy putem vozdeystviya vysokoenergeticheskogo ul'trazvuka na pererabatyvaemoe syr'e [Text] / S. A. Goncharov // Visnyk Kryvorizkoho tekhnichnoho universytetu. – 2009. – Issue 23. – P. 236–239.
6. Gzogyan, T. N. Teoreticheskie i eksperimental'nye issledovaniya polucheniya vysokokachestvennyh kontsentratov [Text] / T. N. Gzogyan // Gorniy informatsionno-analiticheskiy byulleten'. – 2010. – Issue 4. – P. 389–393.
7. Podgorodetskiy, N. S. Avtomaticheskoe upravlenie protsessom raskrytiya poleznogo komponenta pri izmel'chenii rudy [Text] / N. S. Podgorodetskiy // Visnyk Kryvorizkoho tekhnichnoho universytetu. – 2007. – Issue 19. – P. 120–124.
8. Pelevin, A. E. Primenenie grohotov «Derrik» v zamknutom tsikle izmel'cheniya na obogatitel'noy fabrike OAO «Kombinat KMAruda» [Text] / A. E. Pelevin, M. V. Lazebnaya // Obogashchenie rud. – 2009. – Issue 2. – P. 4–8.

9. Shiryaev, A. A. Primenenie tonkogo grohocheniya dlya povysheniya kachestva na obogatitel'noy fabrike gorno-obogatitel'nogo kompleksa «ArselorMitall Krivoy Rog» [Text] / A. A. Shiryaev, E. N. Neskoromniy, A. I. Mironenko, S. A. Samohina, S. S. Staryh // Visnyk KNU. – 2013. – Issue 34. – P. 114–120.
10. Oliinyk, T. A. Osoblyvosti zbahachennia zaliznykh rud [Text] / T. A. Oliinyk, M. O. Oliinyk, L. V. Skliar, A. Yu. Skliar // Zbahachennia korysnykh kopalyn. – 2017. – Issue 67 (108). – P. 88–101.
11. Gubin, G. G. Obobshchenie i analiz vozmozhnosti ispol'zovaniya ul'trazvukovyh kolebaniy pri pererabotke poleznyh iskopaemyh [Text] / G. G. Gubin, T. P. Yarosh, L. V. Sklyar // Zbahachennia korysnykh kopalyn. – 2016. – Issue 62 (103). – P. 132–143.
12. Cao, Q. Surface cleaning and oxidative effects of ultrasonication on the flotation of oxidized pyrite [Text] / Q. Cao, J. Cheng, Q. Feng, S. Wen, B. Luo // Powder Technology. – 2017. – Vol. 311. – P. 390–397. doi: 10.1016/j.powtec.2017.01.069
13. Saikia, B. K. Ultrasonic assisted cleaning of high sulphur Indian coals in water and mixed alkali [Text] / B. K. Saikia, A. M. Dutta, L. Saikia, S. Ahmed, B. P. Baruah // Fuel Processing Technology. – 2014. – Vol. 123. – P. 107–113. doi: 10.1016/j.fuproc.2014.01.037
14. Yusof, N. S. M. Physical and chemical effects of acoustic cavitation in selected ultrasonic cleaning applications [Text] / N. S. M. Yusof, B. Babgi, Y. Alghamdi, M. Aksu, J. Madhavan, M. Ashokkumar // Ultrasonics Sonochemistry. – 2016. – Vol. 29. – P. 568–576. doi: 10.1016/j.ultsonch.2015.06.013
15. Ambedkar, B. Ultrasonic coal-wash for de-sulfurization [Text] / B. Ambedkar, R. Nagarajan, S. Jayanti // Ultrasonics Sonochemistry. – 2011. – Vol. 18, Issue 3. – P. 718–726. doi: 10.1016/j.ultsonch.2010.09.006
16. Morkun, V. Optimization of high-energy ultrasound source parameters for cavitation disintegration of ore floccules before floatation [Text] / V. Morkun, V. Tron, V. Ravinskaia // IEEE International Young Scientists Forum on Applied Physics and Engineering. – 2017. – P. 96–99.
17. Tabei, M. Ak-space method for coupled first-order acoustic propagation equations [Text] / M. Tabei, T. D. Mast, R. C. Waag // The Journal of the Acoustical Society of America. – 2002. – Vol. 111, Issue 1. – P. 53–63. doi: 10.1121/1.1421344
18. Pierce, D. Acoustics: an introduction to its physical principles and applications [Text] / D. Pierce. – NY: Acoustical Society of America, 1989. – 678 p.
19. Mast, T. D. A k-space method for large-scale models of wave propagation in tissue [Text] / T. D. Mast, L. P. Souriau, D.-L. D. Liu, M. Tabei, A. I. Nachman, R. C. Waag // IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control. – 2001. – Vol. 48, Issue 2. – P. 341–354. doi: 10.1109/58.911717
20. Fornberg, B. A practical guide to pseudospectral methods [Text] / B. Fornberg. – Cambridge: Cambridge University Press, 1996. – 231 p. doi: 10.1017/cbo9780511626357
21. Wojcik, G. Pseudospectral methods for large-scale bioacoustic models [Text] / G. Wojcik, B. Fomberg, R. Waag, L. Carcione, J. Mould, L. Nikodym, T. Driscoll // 1997 IEEE Ultrasonics Symposium Proceedings. An International Symposium (Cat. No.97CH36118). – 1997. doi: 10.1109/ultsym.1997.661861
22. Mickens, R. A. Nonstandard finite difference models of differential equations [Text] / R. A. Mickens. – Singapore: World Scientific, 1993. – 264 p. doi: 10.1142/2081
23. Morkun, V. The adaptive control for intensity of ultrasonic influence on iron ore pulp [Text] / V. Morkun, N. Morkun, A. Pikilnyak // Metallurgical and Mining Industry. – 2014. – Issue 6. – P. 8–11.
24. Soneson, J. HIFU Simulator v1.2 [Electronic resource] / J. Soneson // Available at: http://www.mathworks.com/matlabcentral/fileexchange/30886-high-intensity-focused-ultrasound-simulator
25. Vlasko-Vlasov, V. K. Kolyvannia monopoliarnykh domennykh stinok v pole ultrazvukovoi khvyli [Text] / V. K. Vlasko-Vlasov, O. A. Tykhomyrov // Fizyka tverdoho tila. – 1991. – Vol. 33, Issue 12. – P. 3498–3501.
26. Kyrenskyi, L. V. Vplyv ultrazvuku na mahnitni vlastyvosti feromahnetykiv pry riznykh temperaturakh [Text] / L. V. Kyrenskyi, A. I. Drokyn, V. S. Cherkashyn // Mahnitna struktura feromahnetykiv. – 1960. – P. 165–173.
27. Wooh, S.-C. Optimization of Ultrasonic Phased Arrays [Text] / S.-C. Wooh, Y. Shi // Review of Progress in Quantitative Nondestructive Evaluation. – 1998. – P. 883–890. doi: 10.1007/978-1-4615-5339-7_114
28. Silk, M. G. Ultrasonic transducers for nondestructive testing [Text] / M. G. Silk. – Bristol: Adam Hilger Ltd, 1984. – 176 p.
29. Rozenberg, L. D. Fizicheskie osnovy ul'trazvukovoy tekhnologii [Text] / L. D. Rozenberg. – Moscow: Nauka, 1970. – 678 p.
30. Kur'yakov, V. N. Issledovanie vozdeystviya ul'trazvukovogo dispergirovaniya na kinetiku agregatsii asfal'tenov v model'nyh sistemah [Text] / V. N. Kur'yakov // Georesursy, geoenergetika, geopolitika. – 2013. – Issue 2 (8). – P. 22–30.
31. Golik, V. Metal deposits combined development experience [Text] / V. Golik, V. Komashchenko, V. Morkun, O. Burdzieva // Metallurgical and Mining Industry. – 2015. – Issue 6. – P. 591–594.
32. Morkun, V. Automation of iron ore raw materials beneficiation with the operational recognition of its varieties in process streams [Text] / V. Morkun, V. Tron // Metallurgical and Mining Industry. – 2014. – Issue 6. – P. 4–7.

33. Norori-McCormac, A. The effect of particle size distribution on froth stability in flotation [Text] / A. Norori-McCormac, P. R. Brito-Parada, K. Hadler, K. Cole, J. J. Cilliers // Separation and Purification Technology. – 2017. – Vol. 184. – P. 240–247. doi: 10.1016/j.seppur.2017.04.022
34. Sahoo, H. Role of silica and alumina content in the flotation of iron ores [Text] / H. Sahoo, S. S. Rath, D. S. Rao, B. K. Mishra, B. Das // International Journal of Mineral Processing. – 2016. – Vol. 148. – P. 83–91. doi: 10.1016/j.minpro.2016.01.021
35. Morkun, V. Ore preparation multi-criteria energy-efficient automated control with considering the ecological and economic factors [Text] / V. Morkun, V. Tron // Metallurgical and Mining Industry. – 2014. – Issue 5. – P. 4–7.
36. Kupin, A. Research of properties of conditionality of task to optimization of processes of concentrating technology is on the basis of application of neural networks [Text] / A. Kupin // Metallurgical and Mining Industry. – 2014. – Issue 4. – P. 51–55.
37. Yu, J. Beneficiation of an iron ore fines by magnetization roasting and magnetic separation [Text] / J. Yu, Y. Han, Y. Li, P. Gao // International Journal of Mineral Processing. – 2017. – Vol. 168. – P. 102–108. doi: 10.1016/j.minpro.2017.09.012
38. Morkun, V. Model synthesis of nonlinear nonstationary dynamical systems in concentrating production using Volterra kernel transformation [Text] / V. Morkun, N. Morkun, V. Tron // Metallurgical and Mining Industry. – 2015. – Issue 10. – P. 6–9.
39. Ebadnejad, A. Investigating of the effect of ore work index and particle size on the grinding modeling of some copper sulphide ores [Text] / A. Ebadnejad // Journal of Materials Research and Technology. – 2016. – Vol. 5, Issue 2. – P. 101–110. doi: 10.1016/j.jmrt.2015.05.002
40. Morkun, V. Distributed closed-loop control formation for technological line of iron ore raw materials beneficiation [Text] / V. Morkun, N. Morkun, V. Tron // Metallurgical and Mining Industry. – 2015. – Issue 7. – P. 16–19.
41. Wołosiewicz-Głąb, M. Construction of the electromagnetic mill with the grinding system, classification of crushed minerals and the control system [Text] / M. Wołosiewicz-Głąb, S. Ogonowski, D. Foszcz // IFAC-PapersOnLine. – 2016. – Vol. 49, Issue 20. – P. 67–71. doi: 10.1016/j.ifacol.2016.10.098
42. Morkun, V. Formalization and frequency analysis of robust control of ore beneficiation technological processes under parametric [Text] / V. Morkun, N. Morkun, V. Tron // Metallurgical and Mining Industry. – 2015. – Issue 5. – P. 7–11.