ТЕХНИЧЕСКИЕ НАУКИ

ENGINEERING

Если бы я захотел читать, еще не зная букв, это было бы бессмыслицей.
Точно так же, если бы я захотел судить о явлениях природы,
не имея никакого представления о началах вещей, это было бы такой же бессмыслицей.
Михаил ЛОМОНОСОВ

ASSESSMENT OF IRON ORE CONCENTRATION CHARACTERISTICS ON THE BASIS OF ULTRASONIC MEASUREMENTS

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A great number of various factors to a different extent impact iron ore treatment, properties of mineral composition of ore and parameters of technological equipment being some of them. To solve the problem of improving performance of a concentration plant in terms of the concentrate, it is required to elaborate effective scheduled procedures, upgrade technological equipment, develop methods of control over concentration processes considering technological properties of ore fed. There is suggested a method of improving efficiency of magnetic concentration of iron ore under the action of high-intensity ultrasound. There are established dependencies between physical-mechanical and chemical-mineralogical characteristics of iron ore slurry solids and their behavior in technological flows under controlled ultrasonic vibrations, this enabling simulation modelling of the process and specification of optimal controlling actions. The research object is assessment of characteristics and control of iron ore magnetic concentration on the technological line of the ore concentration plant. The research subject is the cyber-physical system based on using impacts of high-intensity ultrasound on slurry solids to assess characteristics

Introduction

A variety of factors influence iron ore treatment with the following groups distinguished [1–5]: characteristics of mineral composition of ore; parameters of crushing equipment to determine the size reduction degree of ground ore; parameters defining grinding indices; and parameters determining flotation. On assumption of these groups, the following basic trends of solving the problems of improving efficiency of the concentration plant in terms of the end product can be singled out [6–9]: development of efficient scheduled procedures of the process and improvement of technological equipment; development of automated systems of controlling technological processes of concentration considering technological properties of ore fed; creation of the system of automated control over critical modes of technological processes and the expert system of decision support.

The resulting separation characteristic with the working point in the optimal separation boundary is an essential index of improving the technological line of ore concentration [10–12]. As in technological flows of the ore concentration line on its various stages, there can be processed different types of ore materials in terms of their physical-mechanical and chemical-mineralogical characteristics, it is expedient to investigate into formation of a separation characteristics of technological concentration processes on the basis of operating data on dynamics of their parameters [13; 14].

Problem statement

The research is aimed at developing a method of improving efficiency of iron ore magnetic separation on the basis of assessment of ground ore particles behaviour under the action of high-intensity ultrasonic vibrations.

Review of the literature

Description of ultrasonic radiation propagation with the set frequency through the

of iron ore magnetic concentration. Obtained dependencies and mathematical models of the non-linear spatial process of high-intensity ultrasound propagation in the iron ore slurry enable implementing the method of assessing characteristics of iron ore magnetic concentration and due to this increase efficiency of the mentioned operations. There are suggested methods of calculating intensity of high-intensity ultrasound in a certain point of the measurement area in order to perform forecast displacement of ground ore particles and changes of the fraction composition of slurry solids under the controlled action of high-intensity ultrasonic vibrations. The developed method and the software-engineering complex for its implementation enable restoring a function of distributing ground ore particles by sizes, forecasting results of technological operations and forming controlling actions.

KEYWORDS:

iron ore, magnetic concentration, simulation modelling, ultrasound, forecasting, technological flows, optimal control.

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mono-disperse slurry, the solid phase of which is composed of particles of certain radius, was considered in the paper [15]. To simulate the process of propagating ultrasonic oscillations with varied velocity of ultrasound propagation and density of the random-heterogeneous medium, papers [16; 17] suggest a method of modelling the first- and second-order k-space.

The results of developing methods of forming control with constraints focusing on the issue of robust decentralized control based on linear matrix inequalities considering the constraints with available quantizes and nonlinear elements were highlighted in the paper [18]. Theoretical and practical results of investigations into nonparametric identification of calculating convulsions and derivatives of kernel functions, kernel estimates of probability density and its derivatives, were presented in the paper [19].

In the paper [20] methods of robust identification of controlled objects by means of kernel regression models, studies the method of adapting weight factors providing were considered and practical recommendations for their calculations were provided.

The research results based on calculation experiments of properties of kernel, exponential and nonparametric smoothing algorithms to solve forecasting problems were presented in papers [21; 22].

In papers [24; 25] results of identifying nonlinear systems by using fuzzy logic and neural networks were discussed. Approaches to forming fuzzy control over various types of technical systems were considered in the paper [25].

Formation of fuzzy models of industrial systems in order to improve their control quality and efficiency were investigated in the paper [26]. There are revealed advantages of methods based on fuzzy logic applied to improving the technology and controlling industrial objects.

Analysis of researches into increasing efficiency of iron ore magnetic concentration reveals a great number of scientific works concerning investigation into, mathematical and simulation modelling and formalization of regularities of iron ore magnetic concentration. In particular [1; 4–6] present some results of applying the mentioned regularities to improving magnetic concentration processes under uncertainty conditions. Besides, it should be noted that application of mentioned methods and tools requires corresponding mathematical toolkit to formalize regularities of distributing slurry solids by sizes and the useful component content in technological aggregates. There are also topical issues of development of the suggested methods of improving controlling actions, obtainment of required data and the technology of iron ore concentration by using the ultrasonic and magnetic fields in order to solve the problem of receiving high indices of useful component extraction and high-quality iron ore concentrate required for metallurgy along with maximal reduction of material and labor expenses.

Materials and methods

To improve efficiency of iron ore concentration and quality of magnetite concentrate, the authors suggest application of spatial impacts of dynamic effects of the controlled high-intensity ultrasound on solid phase particles of the slurry in input products of technological aggregates, this enabling assessment of displacement of ground ore particles and changes in fraction composition of ore slurry solids under the action of these factors in order to forecast results of technological operations and form controlling actions. Simultaneously, it is necessary to take account of a great number of parameters of iron ore concentration, this fact making the model synthesis much more complicated. Fig. 1 shows a typical scheme of an apparatus chain based on a typical technological line of the ore concentration plant.

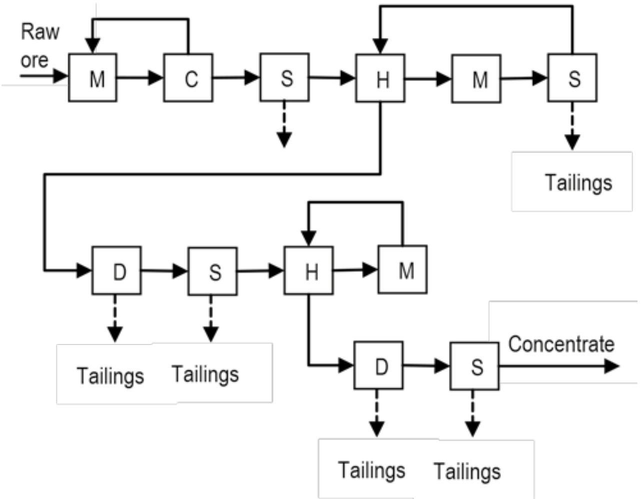

Fig. 1. Structural scheme of a technological line of iron ore concentration: M – mill, C – classifier; S – magnetic separator; H – hydrocyclone; D – deslimer

To form optimal distributed control over the technological line of concentration, it is expedient to obtain data on useful component distribution in ground ore particles from different size classes. To implement continuous contact-free control over this parameter in the slurry flow, we suggest a method based on ultrasonic measurements with high-intensity ultrasound impacting ground ore particles to directly control their shifting into the measurement area. The character of changes in concentration and sizing of particles in the high-intensity ultrasonic field depends on their density and radiation frequency and intensity [4; 10].

An expression for radiation pressure force presented through full and differential sections of ultrasonic wave dispersion and absorption on particles was provided in the paper [4]

$$F_r = \frac{I}{c}\left(\sigma_p + \sigma_s \mu\right), \tag{1}$$

where I is intensity of the incident wave; c is velocity of its propagation; $\mu = \frac{2\pi}{\sigma_s}\int_{-1}^{1} d\cos v \frac{d\sigma}{d\Omega}(\cos v)(1-\cos v)$.

For spherical particles of r radius, the differential effective section of dispersion looks like

$$\frac{d\sigma}{d\Omega}\left(\cos v\right) = \frac{r^2}{9}\left(kr\right)^4\left(a_1 - \frac{3}{2}a_2\cos v\right)^2, \tag{2}$$

where $a_1 = 1-\left(rc^2/\rho_т c_т^2\right)$; $a_2 = 2\left(\rho_т - \rho/2\rho_т + \rho\right)$; $\rho_т$, $c_т$ is particle density and ultrasound velocity in the particle material; $\sigma_p << \sigma_s$, so

$$F_r = \frac{4}{9}\pi r^2\left(kr\right)^4\left(a_1^2 + a_1 a_2 + \frac{3}{4}a_2^2\right)\frac{I}{c} \tag{3}$$

The dependency of the displacement velocity of a particle from its coordinate Z can be presented as [10]

$$V_r(Z) = \beta e^{\alpha z}, \tag{4}$$

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

Under the action of high-intensity ultrasound, there appears radiation pressure changing the granulometric characteristic of the slurry solid phase in the controlled area. With increased intensity of high-intensity ultrasound from zero to a certain value and the constant speed of the slurry flow, either all or certain size classes of the ground material can be displaced into this area:

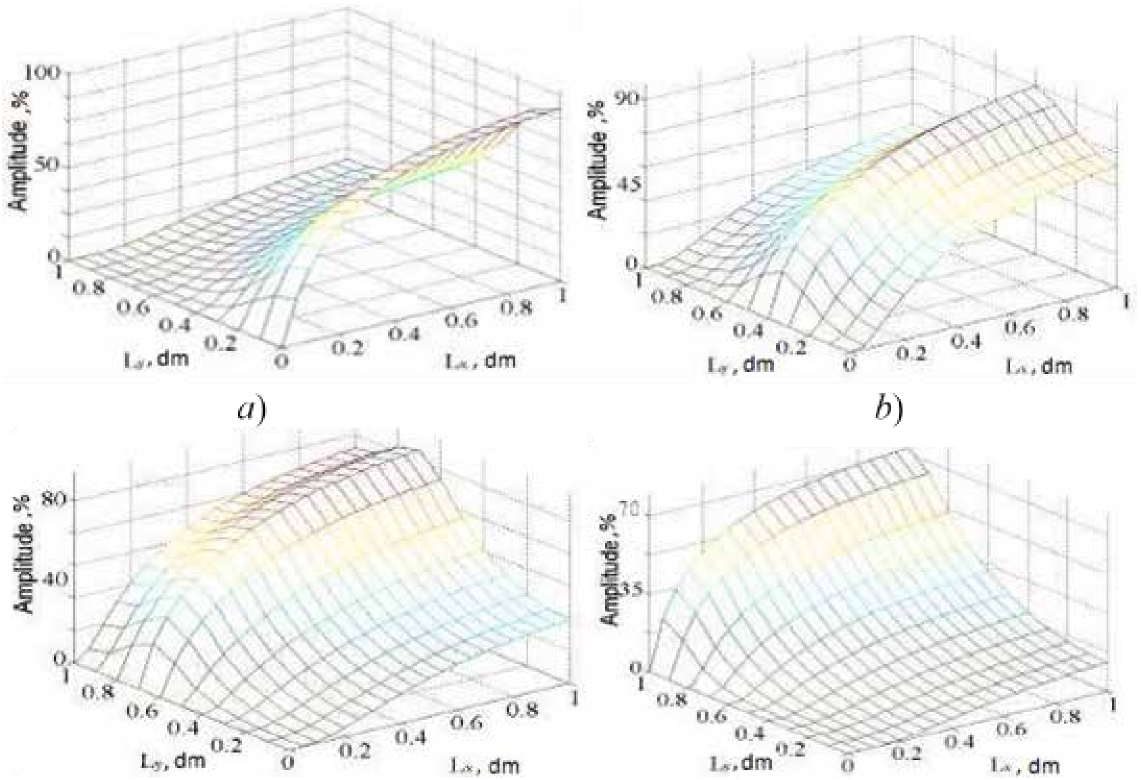

Fig. 2. Results of spatial modelling of pressure changes in the impulse front of high-intensity ultrasound of finite duration propagating in the slurry flow

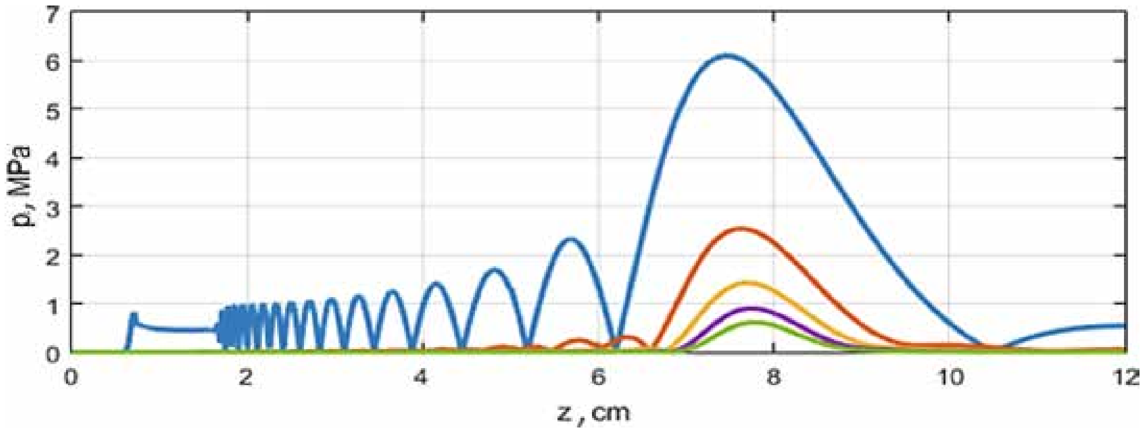

Fig. 3. Axial distribution of pressure of five first harmonics of ultrasonic radiation

$$F(r) = \left(\int_0^{r_1} f(r) r^3 dr + \int_{r_1}^{r_2} f(r) r^3 dr + \ldots + \int_{r_{m-1}}^{r_m} f(r) r^3 dr \right) \Big/ \int_0^{r_m} f(r) r^3 dr \quad (5)$$

The results of spatial modelling of pressure changes in the impulse front of high-intensity ultrasound of finite duration propagating in the slurry flow with sampling interval of $7 \cdot 10^{-5}$ s between each pair Fig. 2, *a* and Fig. 2, *b*, Fig. 2, *b* and Fig. 2, *c*, Fig. 2, *c* and Fig. 2, *d*.

Numerical characteristics of the ultrasonic impulse propagating in the slurry are received by means of the HIFU Simulator v1.2 (Fig. 3).

The amplitude of the ultrasonic wave of v frequency that covers the distance *z* in the slurry can be described by the expression [4; 10],

$$A_v(z) = A_B \exp\left\{ -\frac{zn}{V} \int_0^{r_m} \sigma(v, r) f(r) d \right\}, \quad (6)$$

where *n* is the number of particles in the effective

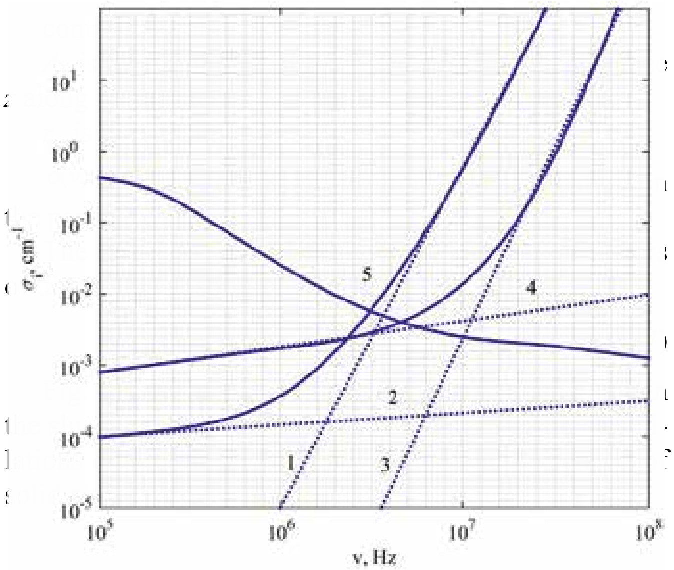

Fig. 4. *Dependency of frequency of components σ_i on that of ultrasonic oscillations: 1,3 – components conditioned by dispersion on solid particles; 2,4 –components conditioned by absorption by solid particles; 5 – components of attenuation by air bubbles; 1,2 – $\bar{r}$ = 0.01 cm; 3,4 – $\bar{r}$ = 0.001 cm*

Here are given frequencies V_{k1} and V_{k2} that are expedient to use for measuring solid particles with mean 10^{-2} and 10^{-3} cm respectively. The density values V_k do not depend on concentration of particles.

Application of the measuring channel based on high-frequency ultrasonic waves [4; 10] enables measurements of the controlled size class of the ground ore. In the high frequency area, when $\sigma(v_2, r) \approx \sigma_s,$ the value

$$S_2 = \ln(A_{0_2} / A_{v_2}) = Z_2 N \int_o^{r_m} F(r) \sigma_s(v_1, r) = \frac{Z_2 W}{\aleph} \int_o^{r_m} F(r) \sigma_s(v_2, r)\, dr \quad (8)$$

is measured.

In this expression,

$$\aleph = 4/3 \pi r^3 \int_o^{r_m} F(r) dr. \quad (9)$$

To obtain a value proportionate to solid phase concentration, Lamb waves can be used. The resulted signal is proportionate to the volume fraction of the solid in the slurry *W* and is not dependent on concentration of air bubbles

$$S_2 = \ln\left(\frac{I^*_{l,v}}{I_{l,v}}\right) = W \frac{[\rho_т - \rho_в] C_v l}{\rho} \quad (10)$$

where

$$I_{l,v} = I^*_{l,v} \exp\left\{ -W \frac{[\rho_т - \rho_в]}{\rho} C_v l \right\} \quad (11)$$

The value S characterizes granulometric composition of the controlled medium

$$S = \frac{S_1}{S_2} = \frac{Z\rho}{l C_v \aleph (\rho_т - \rho_в)} \int_0^{r_m} \sigma(v, r) F(r) dr \quad (12)$$

The value S depends only on distribution of solids by sizes and thus determines concentration of the controlled size class of solid phase particles and, besides, does not depend on concentration of the gas phase in the slurry, i.e. in this case, there is no need for preliminary degasing of the slurry.

Results

Fig. 5 presents results of simulating the displacement trajectory of ore particles of three size fractions in the slurry flow under radiation pressure of high-intensity ultrasound [27–29]. Locations of particles of each size on the tenth step are connected with continuous lines.

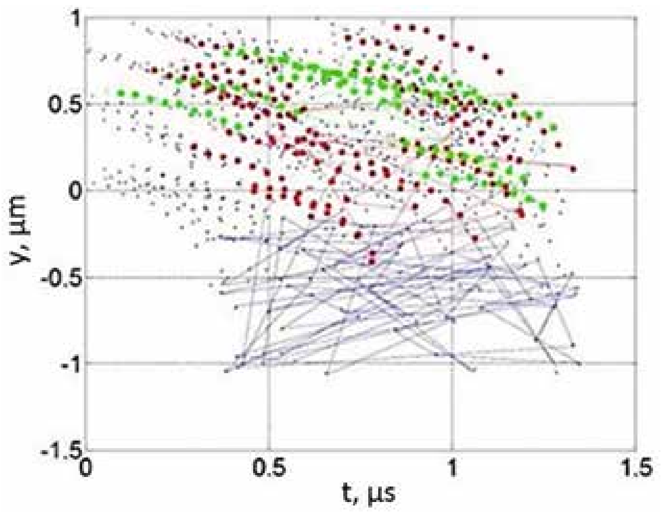

Fig. 5. Resuls of simulating displacement of ore particles of three radii under radiation pressure of high-intensity ultrasound

The method enables calculation of intensity of high-intensity ultrasound in a certain point of the measurement area, thus allowing forecast displacement of ground ore particles and changes of fraction composition of solids in the slurry under the controlled action of radiation pressure of high-intensity ultrasound. The mean-square deviation of the model and the experiment in controlled points of the granulometric characteristic makes 1.76%.

The suggested method of assessing the function of distributing the useful component by size classes of ground ore particles in the slurry flow on the basis of measuring parameters of propagation of high-intensity ultrasonic waves and Lamb waves is different from the existing ones in the fact that during measurements ground ore particles of certain size and density are displaced into the measurement area by subjecting the slurry to high-intensity ultrasound. The obtained results enable forecasting distribution of iron ore solids and forming controlling actions on this basis.

The developed theoretical, algorithmic and software-engineering solutions were tested on experimental installations of enterprises Ukrrudprom and Rudpromheofizyka.

The technical tools of ultrasonic and radiometric control were connected to a computer by means of a highly precise 24-bit analog-to-digital convertor ZET 230 by the interface USB 2.0. The convertor frequency for each channel of the module ZET 230 was up to 100 kHz, the maximum input voltage was ± 10 V, the maintained exchange speeds were from 75 to 115200bps. In the frequency range of 10Hz-20Hz and the dynamic range of 100dB, the maximum irregularity of the amplitude-frequency response of the module ZET 230 was 1dB.

The function of distributing ground particles by sizes and density (the useful component content) was assessed by their redistribution in the slurry flow under the radiation pressure of high-intensity ultrasound. There was determined intensity of ultrasonic waves of 5MHz frequency and Lamb waves of 1MHz frequency that passed through the analyzed medium.

Dependencies obtained during experiments were identified by means of GUI modules of Fuzzy Logic Toolbox of MATLAB. On this stage, the number of the model inputs and outputs as well as the number of terms and types of membership functions was determined.

The knowledge base was formed from the results of measuring concentration of the slurry solid phase, concentration of the controlled size class of the solid phase particles and the signal that corresponds to the current acoustic power radiating into the slurry flow by the working waveguide. The algorithm of three-term lattice partition was used for assessing each input variable with the Gaussian membership function. The model structure is in Fig. 6.

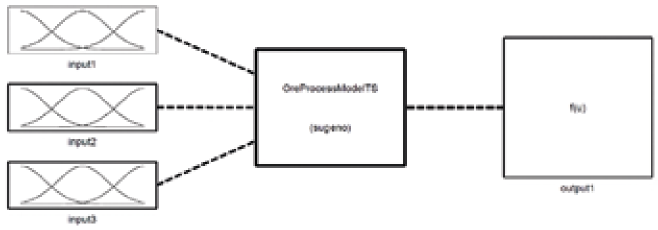

Fig. 6. Structural scheme of the fuzzy model

The simulation was aimed at reproducing the (sieve) characteristic of products of technological aggregates. Fig. 7 reveals the results of model training.

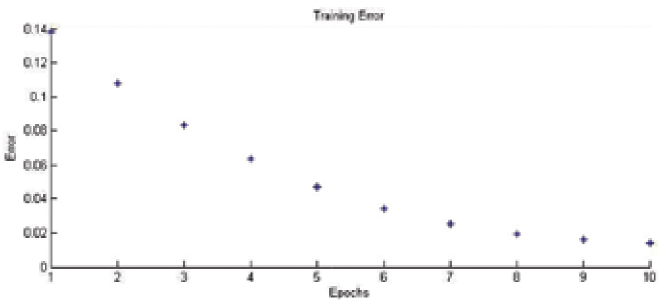

Fig. 7. Results of training the model TS3312

While investigating, the authors considered such fractions of ore particles: +3. 3 + 1. 1 + 0.5, 0.5 + 0.25, 0.25 + 0.125, 0.125 + 0.071, 0.071 + 0.056, 0.056 + +0.044, 0.044 + 0. The general output of functions by sizes was determined by the formulae: for the fraction $r[d_1]-R[>d_1]=r[d_1]$, for the fraction $r[d_i]$ – $R[>d_i]=r[d_1]+r[d_2]+\ldots+r[d_i]$; for the fraction $r[d_m]$ – $R[>d_m]=1$. Fig. 8 shows granulometric (seave) characteristics of products of technological aggregates restored according to the simulation results.

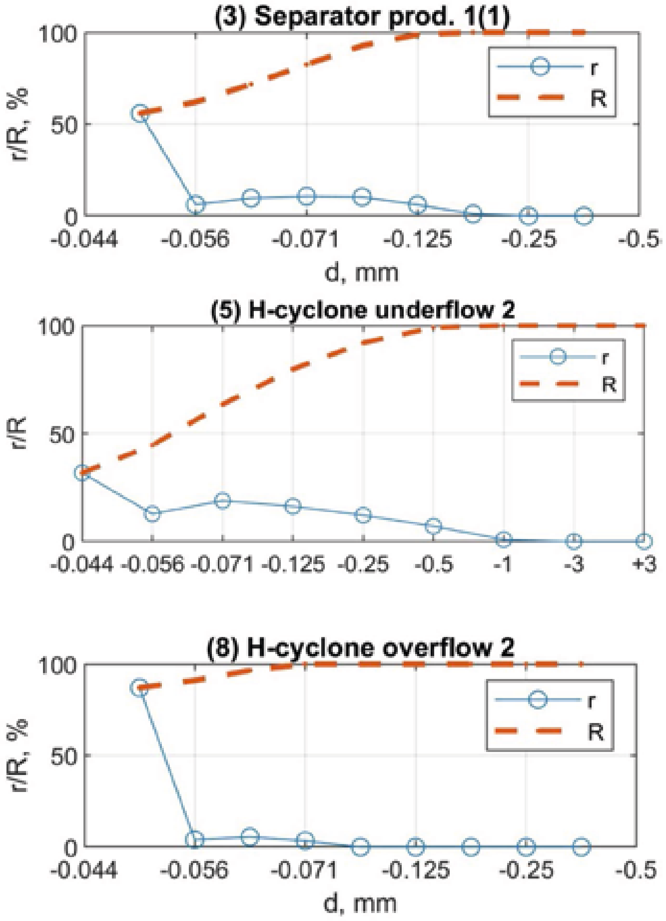

Fig. 8. Sieve characteristics of products of technological aggregates

The conducted analysis confirmed reproductively of the results obtained. The error of restoring the function of distributing ground particles by sizes and density in the mean-square deviation is 1.8–2.35 %.

The developed method and the software-engineering complex implementing it enable correct restoration of the function of distributing ground ore particles by sizes, forecasting of the results of technological operations and formation of controlling actions.

Conclusion

The developed cyber-physical system of assessing efficiency of iron ore magnetic concentration provides formation and maintenance of required characteristics (granulometric composition) of iron ore in products of technological aggregates through forming controlling actions on the basis of results of ultrasonic measurements of slurry parameters and the fuzzy logic output. This enables reduction of the functioning period of technological aggregates irrespective of their optimal characteristics, thus ensuring achievement of required concentration indices along with maximum productivity and energy efficiency.

The obtained dependencies and mathematical models of the nonlinear spatial process of propagating high-intensity ultrasound in the iron ore slurry allow implementing the method of assessing characteristics of iron ore concentration and due to this increasing efficiency of the first-stage magnetic separation by 4.1% and that of the second one – by 5.7%.

The researches results are were applied to designing and introducing the technical and algorithmic support of automated control systems of technological processes at mining enterprises of the Association Ukrrudprom.

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ОЦЕНКА ХАРАКТЕРИСТИК КОНЦЕНТРАЦИИ ЖЕЛЕЗНОЙ РУДЫ НА ОСНОВЕ УЛЬТРАЗВУКОВЫХ ИЗМЕРЕНИЙ

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Реферат. На процесс переработки железорудного сырья в разной степени влияет большое количество различных факторов, в частности, характеристики минерального состава руды и параметры технологического оборудования. Для решения задач повышения производительности обогатительной фабрики по концентрату необходима разработка эффективных регламентных условий ведения процесса, совершенствования технологического оборудования, разработка методов управления технологическими процессами с учетом технологических свойств руды, поступающей в переработку.

Предложен метод повышения эффективности процессов магнитного обогащения железной руды на основе оценки поведения частиц измельченной руды под действием радиационного давления ультразвука высокой интенсивности. Установлены зависимости между физико-механическими и химико-минералогическими характеристиками частиц твердой фазы железорудной пульпы и их поведением в технологических потоках под влиянием управляемых ультразвуковых колебаний, на основе которых может быть выполнено имитационное моделирование процесса и определены оптимальные управляющие воздействия.

Полученные зависимости и математические модели нелинейного пространственного процесса распространения ультразвука высокой интенсивности в железорудной пульпе позволили реализовать метод оценки характеристик процессов магнитного обогащения железной руды и за счет этого повысить эффективность упомянутых операций. Предложена методика расчёта интенсивности ультразвука в определённой точке зоны измерений, которая позволяет осуществлять прогнозируемое смещение частиц измельченной руды и изменение фракционного состава твёрдой фазы пульпы под управляемым воздействием радиационного давления ультразвука высокой интенсивности. Разработанный метод и реализующий его программно-технический комплекс позволяют корректно восстанавливать функцию распределения частиц измельченной руды по размерам, а на ее основе прогнозировать результаты технологических операций и формировать управляющие воздействия.

Ключевые слова: железная руда, магнитное обогащение, имитационное моделирование, ультразвук, прогнозирование, технологические потоки, оптимальное управление.

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