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ON NONLINEAR EFFECTS ACCOMPANYING ELECTRIC DISCHARGES IN A HETEROGENEOUS FLUID

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This paper presents various aspects of nonlinear effects and pulse phenomena accompanying electric discharges in a heterogeneous liquid medium. The layout of an electro-hydro-pulse plant and the experimental technique are briefly described. The results of computer processing of current and voltage oscillograms are shown, by which correlation coefficients and the power spectrum are determined. The solution of a system of dynamic equations is given that makes it possible to determine the parameters of the mutually consistent formation of a discharge in a heterogeneous fluid. The authors established an ambiguous impact of a heterogeneous operating fluid on the parameters of the electro-hydro-pulse effect, which in turn also changes its composition and structure.

***Keywords**:* electro-hydro-pulse processing, dispersed product, structure, correlation coefficient, energy spectrum, dynamic equations.

Introduction

The study of the processes taking place at an electrical discharge destruction of solid inorganic materials is both of theoretical and practical interest due to the intensive development of electrical technologies, which are more effective than mechanical methods of material processing. The relevance and applied value of these studies is justified by the need to determine the most optimal, from the standpoint of saving energy costs, modes of processing and crushing of various natural minerals to a desired degree of dispersion. The importance of research on electric discharge breakup is also due to the need to optimize energy costs in such technological processes as destruction of concrete constructions to be utilized, drilling wells in hard rocks, or construction of underground workings for processing plants [1-3]. In addition, the study of the laws governing the formation of an electrical discharge in a heterogeneous multicomponent liquid medium is of interest in the production of new materials with desired properties [4,6].

Developed under the guidance of Professor K. Kussaiynov, the electro-hydro-pulse (EHP) method of breakup and crushing of solid deposits and scale on the surfaces of heat-exchange equipment, as well as the technique of inorganic minerals processing by electric discharges in water, have already been successfully implemented for more than 30 years. The distinction of the proposed EHP technology is that it makes for obtaining not only reduced, but also purified from impurities dispersed product very soon.

Due to high-voltage electrical discharges in an aqueous solution of inorganic materials, phase and structural transformations take place; the operating fluid is satud with steam and gas bubbles and mixes with solid particles. Experiments confirm the ambiguous impact of EHP processing on the composition and structure of the process materials. Moreover, there is a manifestation of feedback coupling in the form of nonlinear effects of heat- and mass transfer phenomena on the amplitude and frequency of pulsed electrical discharges in the operating fluid and, consequently, on the operation of the electric discharge generator. The paper considers the features of EHP processing modes depending on the composition and structure of the operating fluid components in which the electric discharge is performed; examples of its ambiguous impact on the composition and structure of the process materials are given.

1. The experimental part

The layout of the plant for generation and recording of high-voltage pulse actions is shown in Fig. 1. In this layout, the formation of the discharge structure in the dielectric and the operation of the pulsed voltage generator are modeled using an equivalent circuit of an oscillating contour with a delayed pulse generator of *C* electrical capacitance, of *R* resistance, and of *L* inductance. In the course of experiments, the experimenters developed a technique for measuring current pulses with duration of (0.32-0.64) ms using an electron oscillograph [5]. Measurements of pulse current and pressure were carried out at the following parameters of the discharge circuit: voltage U= (3÷30) kV, storage capacity C=0.25μF; an interelectrode distance *l*=(1÷10) mm; a discharge frequency ν=(1.5÷2.0) Hz.

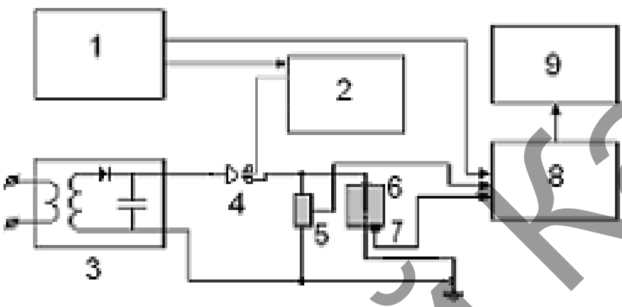


Fig.1. The layout of the electropulse plant and a pressure measuring bench:
1 – a delayed pulse generator, 2 – an ignition block, 3 – a pulse current generator and an energy storage, 4 – a controlled discharger, 5 – a voltage-ratio divider, 6 – a working volume, 7 – a pulse pressure meter, 8 – PCS-500 oscillograph, 9 – a computer.

The inaccuracy of measurements was (3-5) %. When processing by electrical discharges of different frequencies, stable nonlinear signals with stable peaks were observed, Fig. 2 and 3. In time-base sweeps, it was possible to trace some stabilization of the maxima and pulse current signals frequency equalization throughout the entire time range of a discharge spread. The signal pulses (Fig. 3) were obtained at lower electrical discharge rates. In this case, pulses of 0.32 ms, 0.48 ms, 0.64 ms duration aperiodically alternated regardless of the values of the discharge contour parameters.

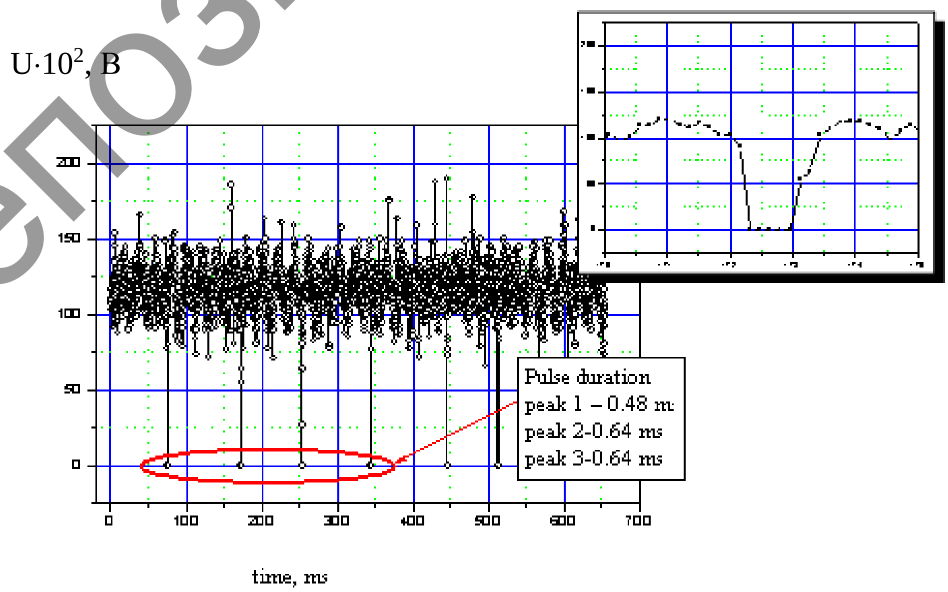


Fig.2. Dependence of U=f(t) at C=0.25 μF, *l*=3 mm.

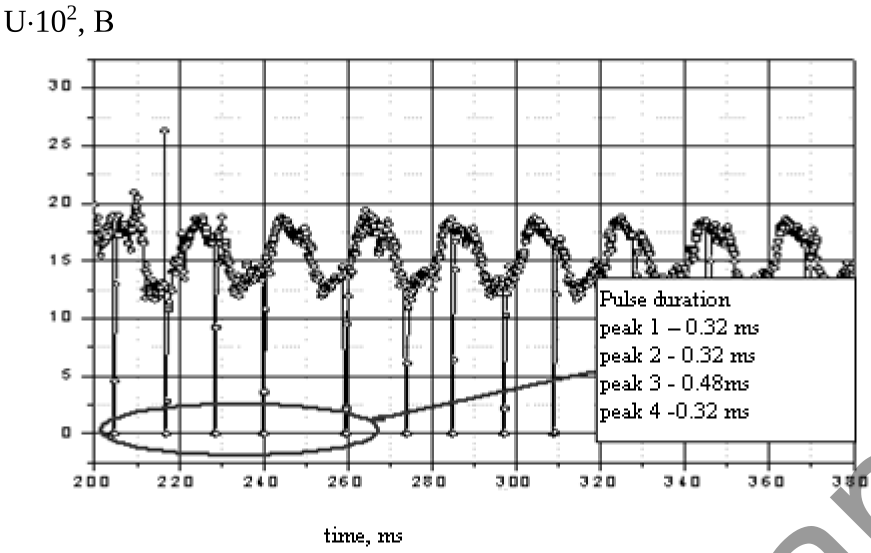
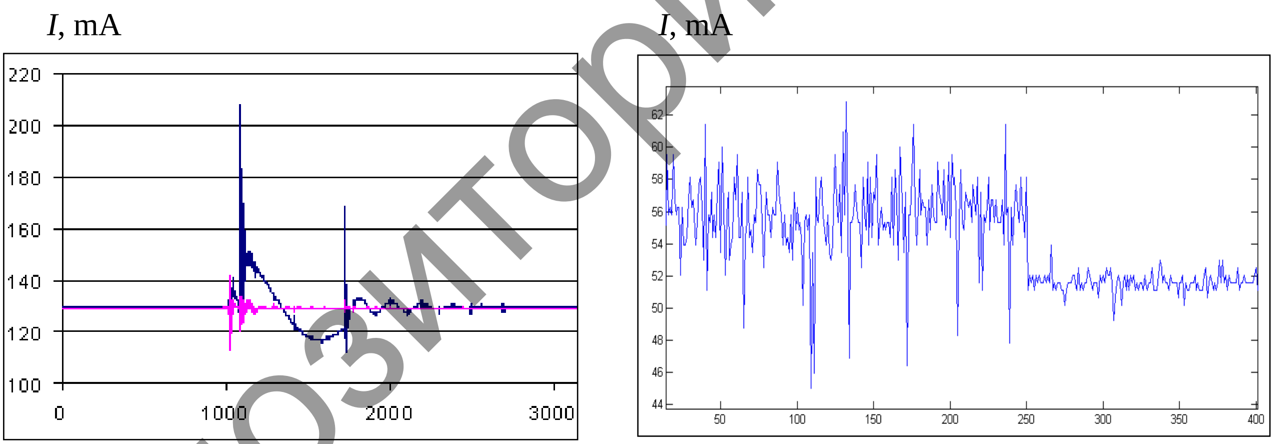


Fig.3. Dependence of U=f(t) at C=0.10μF, *l*=1 mm.

Fig. 4 shows examples of current oscillograms under different EHP action modes. Experiments showed that to achieve optimal conditions ensuring the minimum energy intensity of the electrohydraulic processing, the most important problem was to establish parameters for the mutually consistent formation of the discharge in a heterogeneous medium and the operation of a pulse voltage source.



a) b)

Fig.4. Current oscillograms at: a) – single and b) – repeating electrical discharges of a preset frequency.

This mode corresponds to the so-called "sustained" operating mode of the pulse pressure generator. To determine the mode, the authors carried out computer processing of signals using the MatLab package, where with the built-in functions of the standard functions xcorr (y); E(t)Y=fft(y, N), the correlation coefficients and the power spectrum were calculated [4].

Fig. 5 shows the results of processing of the current oscillogram with an input voltage U=3 kV and a frequency ν=12 Hz. Under the impact of EHP of different frequencies, signals with repetitive stable peaks, and gradual regulation of the maxima and equalizing of the pulse current signal frequency are observed. To study EHP processes more intensively, it is necessary to determine the dependence of the rate and character of the discharge formation, accompanied by the continuous or fast growth of the discharge channels, on the ratio of the generator impedances.

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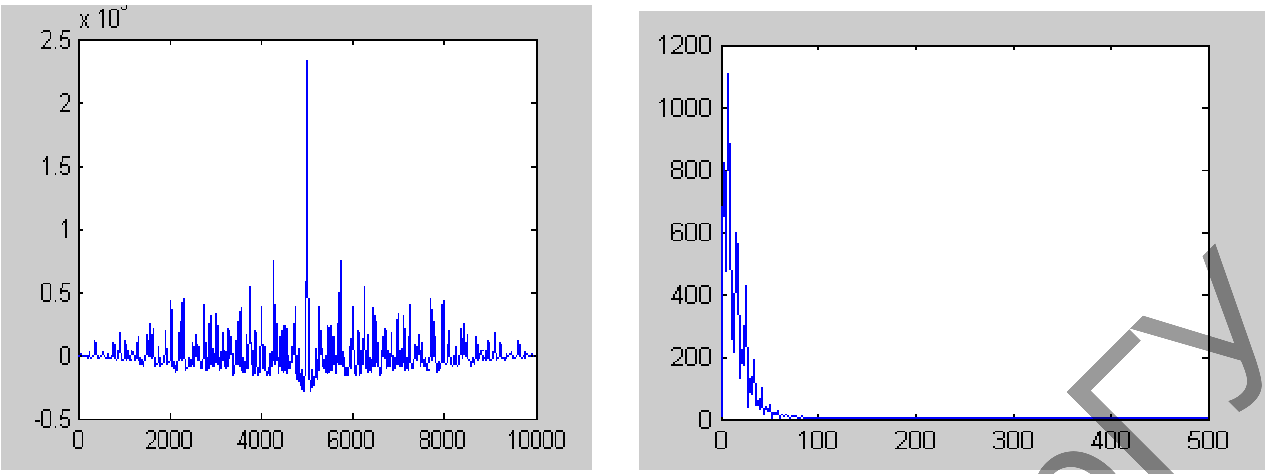

a) b)

Fig. 5. Correlation coefficient (a) and energy spectrum (b) of pulse signals.

The results of the experiments show that to achieve optimal conditions for the crushing of the solid phase with simultaneous making provisions for lower energy requirement for the EHP processing, it is important to establish parameters of the mutually consistent formation of the discharge in a heterogeneous medium and those of the operation of a pulse voltage source. Theoretically, this mode corresponds to the so-called "self-sustaining" operating mode of the pulse pressure generator. To determine it, it is possible to use the solution of the dynamic equations of a nonlinear oscillatory contour [2-4].

2. Stimulation based on solving a system of dynamic equations.

Under the electro-hydraulic effect, the formation of curving and branching discharge channels is of a stochastic character, and it takes place during a very short period of time. The formation of electrical discharge streamers in a liquid medium is of a stochastic character and occurs during a very short period of time. The fractal model of dielectric breakdown to describe quick-changing nonlinear processes accompanying the spread of a single discharge was first applied in [7].

According to [8], in a generator with inertial nonlinearity, auto oscillations in the system are provided by introducing a thermo-resistance R(T) into the oscillatory contour. The properties of the thermo-resistance are nonlinearly dependent on the current flowing through it. The differential equation of current i(t) in the circuit of the oscillatory contour is of the following form

$$\frac{d^2i}{dt^2}+\left[\frac{R(T)}{L}-\frac{M\cdot S_0}{L\cdot C}\right]\cdot\frac{di}{dt}+[(L\cdot C)^{-1}+L^{-1}\cdot\frac{\partial R(T)}{\partial T}\cdot\frac{dT}{dt}]\cdot i=0, \quad (1)$$

where S_0 is the transconductance of the amplifier, which is assumed to be linear, M is the mutual inductance of the feedback circuit, and R(T) is the resistance of the thermistor.

In the case of a linear dependence of the resistance on temperature, i.e. when the heat exchange process proceeds according to Newton's law, it is possible to introduce dimensionless variables and obtain the following system of dynamic equations in dimensionless variables, which describes the dynamics of the current in the circuit of an oscillatory contour:

$$\begin{cases}\dot{x}=m\cdot x+y-x\cdot z;\\ \dot{y}=-x;\\ \dot{z}=-g\cdot z+g\cdot x^2,\end{cases} \quad (2)$$

where x is the current in the circuit of the oscillation contour, y is the current in the feedback circuit, and z is the parameter of the nonlinear translator that provides a delayed signal.

In the three-dimensional two-parameter system described by the system (2), the excitation parameter *m* is proportional to the difference between the carried in and dissipated energies in the contour; the parameter g characterizes the relative time of the thermistor relaxation and is the so-called response time parameter of the generator. The equivalent circuit does not contain nonlinear elements, so using simple transformations the equations can be reduced to the system of equations of the modified generator with inertial nonlinearity and then, in the limit case for $g \to 0$, the initial system (2) degenerates into a two-dimensional one corresponding to the classical Van der Pol generator.

The real generator and the oscillatory circuit are characterized by inertial nonlinearity, and the value range of the response time parameter g is limited by some interval, the parameter values themselves fluctuate. To take into account the nonlinearity in [6], the original system is transformed into the following form:

$$\begin{cases} \dot{x} = (m - \mu \cdot z) \cdot x + y / k(t); \\ \dot{y} = -x; \\ \dot{z} = g(J(x) \cdot x^2 - z), \end{cases} \qquad J(x) = \begin{cases} 1, x > 0 \\ 0, x < 0 \end{cases}, \tag{3}$$

where J(x) is Heaviside unit step function.

In [7] it is indicated that for $g \to 0$ the parameter $d \neq 0$, in this case for a slugged generator the relative frequency of the nonlinear translator g<1. In this case it is desirable to achieve the required mode at values of g>1, and to make an assessment of possible values of the other parameters of the circuit. To obtain the calculated expressions, let us introduce a new parameter μ as a coefficient that regulates the value of the voltage in the feedback circuit z. Then the system of dynamic equations is transformed as follows:

$$\begin{cases} \dot{x} = (m - \mu \cdot z) \cdot x + y / (1 + A \cdot \cos(x)); \\ \dot{y} = -x; \\ \dot{z} = g(J(x) \cdot x^2 - z), \end{cases} \tag{4}$$

where μ is the amplification factor, g is the ratio of the frequency of the nonlinear receiver and the oscillatory contour, with g>1.

The distinction of this system is that instead of the parameter *k(t)*, a function that describes the dynamics of the pulse current in the form of an explicit cosinusoidal dependence, is introduced. This dependence can be interpreted as a mode of supplying a pulse voltage from the generator. The solution of the obtained system of dynamic equations was gained on the base of the fourth-order Runge-Kutta standard method using the MatLab 6/5 package. As a result of the calculations, the time base sweeps of currents and the phase portraits of signals at various initial electrical parameters of the circuit were obtained, Fig. 6.

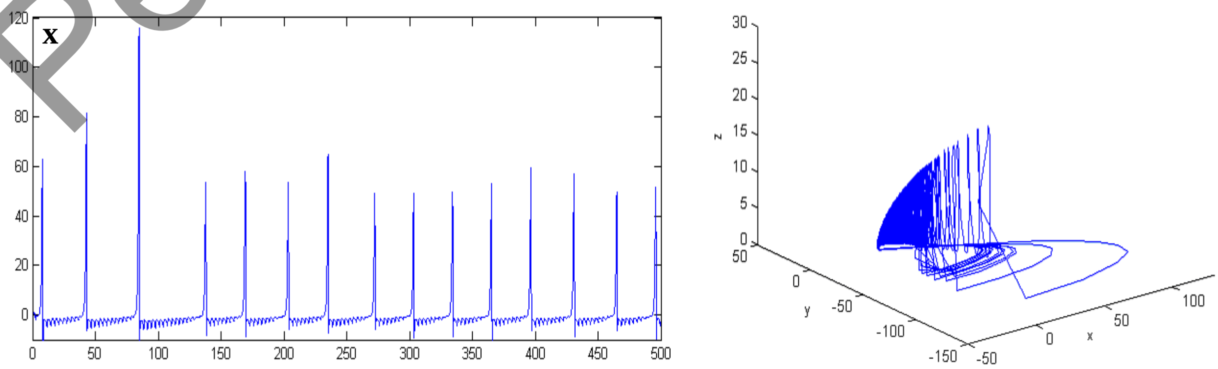

Fig. 6. Pulse signals and phase portraits at: m=2.25; g=2.0; A=0.8; μ=4.0.

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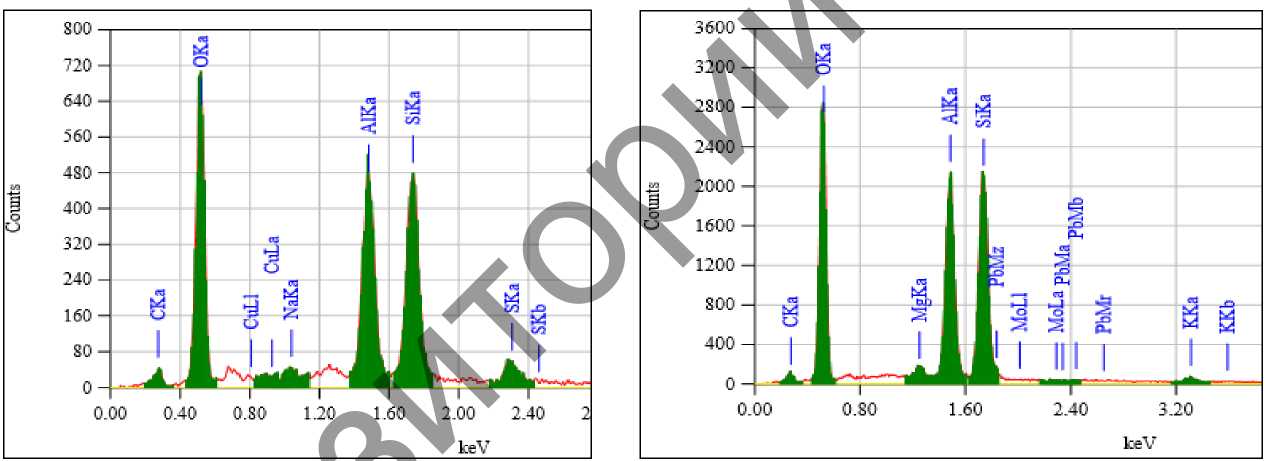
The solution of the system of dynamic equations makes it possible to embrace a wide range of properties and to vary the parameters of the circuit in order to achieve a mutually consistent formation of the discharge and to determine optimal conditions for the EHP processing of a liquid medium, i.e. the parameters of a "self-sustaining" operating mode of the pulse pressure generator.

3. Nonlinear effects of EHP processing impact on the structure and properties of the processed raw materials.

As an operating fluid, which filled the working volume (6) in Fig. 1, the experimenters used aqueous solutions of various natural minerals, carbon powders, technogenic raw materials, etc., which were subjected to EHP. By varying the parameters of the EHP processing, it is possible to change not only the granulometric composition, but also their structure and properties.

EHP processing of samples of raw materials was carried out with a different number of electrical discharges: n=500, 750, 1000, and 1250. Changes in samples of processed raw materials were examined by spectrophotometric analysis at a scanning electron microscope JEOL, JED-2300 in the city of Almaty. The analysis of the microstructure, energy spectra and the dynamics of the content of elements after mechanical and EHP processing shows various changes in the processed samples [9, 10]. Figure 7 shows the energy spectra obtained with the JEOL microscope, on the horizontal axis there are energy values, kev.



a) b)

Fig. 7. Energy spectra of samples of technogenic raw materials of the Nurkazgan mine after: a) mechanical processing; b) electropulse processing at n=1250.

It can be seen from the obtained energy spectra that after the EHP processing, the intensity of the aluminum and silicon lines increased by more than threefold; and clear lines of molybdenum, magnesium, and others appeared there. In general, the results of spectral analysis show the ambiguous impact of different modes of electropulse processing on the concentration of such chemical elements such as C, Na, Mg, K, etc. For example, the concentration of some metals decreases with an increase in the number of electrical discharges. Optimal parameters of EHP processing for obtaining a dispersed product with preset sizes are determined.

To ensure the reliability of the obtained results, the final data on the results of spectral analysis of processed samples of the technogenic raw materials from the Annensk mine on the JEOL raster microscope were determined as the average of 5 repeated measurements. The diagram (Fig.8) shows the dynamics of the elemental composition of raw materials, depending on the mode and type of processing; the values of the mass concentration of elements, %, are plotted on the vertical axis. The results of the spectral analysis of processed samples of technogenic raw materials from the Annensk mine show the maximum aluminum content of 12.53% and silicon to 40.23% after processing with 500 discharges; copper content to 5.27% after processing with 1000 discharges; molybdenum content of 3.85% after processing with 1250 discharges. Conversely, the concentration of magnesium decreases.

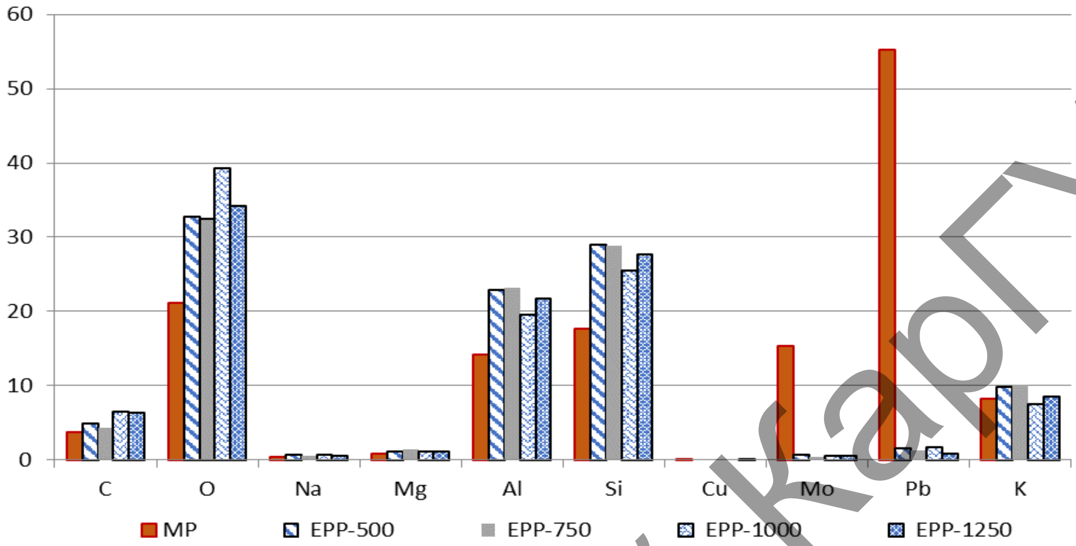


Fig. 8. Change in elemental composition in samples of technogenic raw materials from the Annensk mine after processing: mechanical processing (MP); electric pulses processing (EPP).

Thus, using the electropulse action, it is possible to realize the possibility of additional copper extraction for commercial concentrates from this technogenic raw material, Fig. 9.

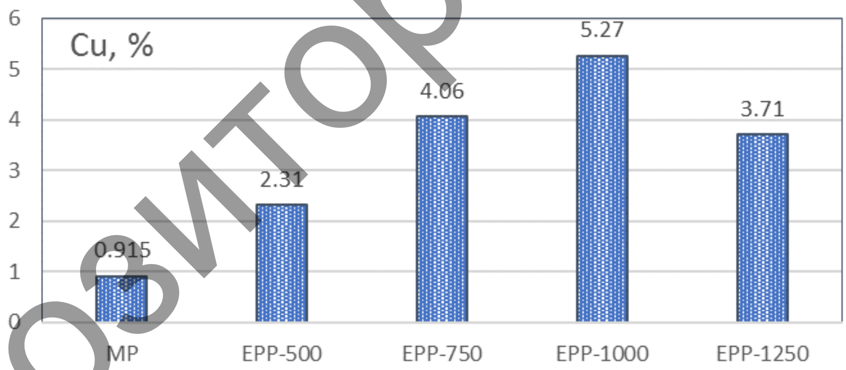


Fig. 9. Dynamics of copper content depending on the number of discharges at electropulse processing of samples of technogenic raw materials from the Annensk mine.

For this purpose, it is necessary to process raw materials at a rate of not more than 1000 pulse discharges, which is enough to increase the copper concentration by almost 5 times compared with the concentration after mechanical crushing. This EHP processing provides ore enrichment and maximum copper extraction. On the spectra of energy intensity, the changes in the main luminescence maxima of individual chemical elements, depending on the mode of electropulse processing are clearly visible. It should be noted that all experiments with different numbers of discharges of electropulse processing were carried out at the same capacities and discharge energies, and the raw material was reduced to fractions of 0.1-0.2 mm.

During experiments, the optimal electro-technical parameters were determined: the inter-electrode distance value, the amount of the supplied energy and the voltage, taking into account the characteristic properties of the processed raw materials. Despite the slight increase in the concentration of elements, in terms of tons of accumulated processed metal-containing and technogenic raw materials in practice, a significant increase in extraction of valuable and necessary elements can be obtained. It should be noted that the obtained results are valid for the raw materials of the mentioned deposits.

Conclusion

The study of nonlinear effects and the demonstration of the structural properties of turbulent mixing at EHP processing of heterogeneous liquids were carried out on the basis of thermodynamic analysis. Knowledge of the mechanism of heat and mass transfer processes in heterogeneous liquids, the intensity of which is mainly determined by the laws of hydrodynamics, is important and necessary to ensure reliable operation and proper design of process equipment.

The characteristic property of EHP processing is that the parameters of electrical discharges depend on the composition of the heterogeneous liquid medium, and, in turn, they change their composition and structure. The results of numerical calculations can be used in practice to compute correlation coefficients of pulse signals and to determine energy spectra. The experiments have shown that the developed EHP technology makes for obtaining a dispersed and purified dispersed product with preset parameters in a short period of time.

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