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High-frequency demagnetization of magnetite suspensions

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Abstract

Purpose. The research purpose is to substantiate the high-frequency demagnetization technology parameters for magnetite suspensions, taking into account the established patterns of changes in the electrical resistivity of circulating water and changes in magnetic field induction depending on the concentration of dissolved salts.

Methods. The circulating water from the processing plant is a part of the magnetite suspension. The change in the electrical conductivity indices of this water was studied under laboratory conditions using the conductometric method with alternating current of various frequencies. The degree of demagnetization of the magnetite particles was determined based on the study of the sedimentation kinetics of both magnetized and demagnetized magnetite suspensions. A special device was used to demagnetize the magnetite particles. It is a solenoid which, together with a capacitor, forms an oscillatory circuit in which damped high-frequency electromagnetic oscillations are periodically generated by current pulses supplied.

Findings. The aspects of the high-frequency electromagnetic field propagation within the magnetite suspension have been revealed, taking into account the field energy dissipation factor and the influence of the suspension technological parameters (electrical resistivity of the circulating water, solid phase concentration) on the characteristics of the electromagnetic field. A relationship between the concentration of magnetite in the suspension and the electromagnetic field dissipation factor has been determined. As a result of determining the sedimentation kinetics, it has been found that the settling rate of the demagnetized magnetite suspension is lower compared to the magnetized one.

Originality. The dependencies of the change in the electrical resistivity of the circulating water from the processing plant on the salt content, as well as the changes in the magnetic field induction along the solenoid axis on the distance from its edge and the surrounding medium, have been obtained. It has been found that to ensure complete demagnetization of magnetite, it should be demagnetized at least twice within the solenoid operating space. This provides a maximum suspension flow velocity of 5.6 m/s, while the sedimentation rate of the demagnetized suspension decreases by a factor of 3.1 compared to the magnetized one. This indicates the effectiveness of demagnetization and the destruction of interparticle magnetic interactions.

Practical implications. The research can serve as a basis for determining rational parameters in the design of high-frequency demagnetizing devices. Their application makes it possible to improve the beneficiation indicators of magnetite ores, bringing them closer to theoretically possible levels, enhancing the efficiency of subsequent classification processes, and reducing the load on grinding equipment.

Keywords: *magnetite, conductometric method, demagnetization, suspension, electrical resistivity, dissipation*

1. Introduction

To date, the demagnetization of magnetite suspensions is a crucial stage in their preparation for further use in mineral processing operations. This is because the production of pure and ultra-pure materials, exceptionally high-quality mineral concentrates, requires maximum homogeneity of the initial raw materials [1], [2]. Enhancing the selectivity and stability of technogenic and natural raw materials processing has been repeatedly emphasized in studies focused on applying mechanochemical, sorption, and thermochemical approaches [3]-[7]. The presence of residual magnetization in the suspension leads to the interaction of particles with each other through secondary magnetic fields, significantly complicating the density-based separation process and reducing the separation efficiency. For this reason, demagnetization and de-electrization are considered mandatory preparatory procedures that ensure the stability of the suspension physicochemical properties, its homogeneity and high separation accuracy at subsequent technological stages. Recent interdisciplinary research has highlighted that achieving high-performance processing parameters in mineral-based industries also depends on integrating adaptive management models, sustainable development frameworks and innovations at the interface of technologies and creative industries [8]-[10].

To ensure the adequate separation of raw material components, it is necessary to create conditions in which each

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material particle is isolated from the influence of neighbouring particles. This will allow for the most accurate implementation of the selectivity principle in the separation process [11], [12]. Similarly, in the beneficiation processes of other types of raw materials, such as copper-containing technogenic materials [13] or ilmenite concentrates [14], achieving high separation accuracy requires eliminating interparticle interactions.

One of the key factors complicating this process is the presence of residual electric and magnetic charges, which are generated due to friction, collisions, or the influence of fields during the previous stages of material preparation [15]. These charges generate secondary fields that cause interactions between particles, promoting aggregation, distortion of movement trajectories, and a decrease in the efficiency of subsequent separation. For this reason, de-electrization and demagnetization are mandatory preparatory procedures before the major separation stage. The primary objective of these processes is to eliminate residual electric and magnetic effects that may cause uncontrolled disturbances in particle distribution [16], [17]. These processes are carried out using alternating electromagnetic fields of sufficiently high frequency, which ensure effective destabilization of residual fields without damaging the particle structure. Such procedures significantly enhance the accuracy and efficiency of subsequent separation processes, provide better quality of the obtained concentrates, and ultimately produce purer and more homogeneous materials for further use in relevant technological areas.

Demagnetization processes are carried out using high-frequency alternating electromagnetic fields, destabilizing residual magnetic moments without disrupting the structure of the particles. This approach makes it possible to improve concentrate quality, reduce the circulating load on mills, and increase the overall energy efficiency of the technology [18], [19].

It should be noted that the magnetization process is not instantaneous [20], [21]. Under the influence of a sufficiently strong constant magnetic field, a ferromagnetic sample becomes magnetized rapidly, though not instantaneously, reaching approximately 70% of its saturation state. The period required for full saturation can reach up to two days, depending on the natural magnetic properties of the sample, provided that the constant magnetic field acts continuously. If the sample is exposed to a low-frequency (≈ 1 Hz) alternating magnetic field, it will never reach magnetic saturation. As the alternating magnetic field frequency increases, the magnetization will accordingly decrease. At high magnetic field frequencies, magnetization will be absent, since the magnetic domains will not have time to orient themselves along the lines of the external magnetic field. Magnetization experiments have shown that this trend is generally observed; however, specific nuances arise due to the influence of eddy current fields [22], [23]. Such phenomena are significant when designing and modelling new magnetic systems or studying thermal and magnetic properties of alloys [24]-[27]. For example, increasing the magnetic field frequency in ferromagnets leads to a noticeable widening of the dynamic hysteresis loop. This phenomenon is caused not only by the inertia of domain walls, but also by the emergence and intense development of eddy currents inside the material. Eddy currents, which arise due to the alternating magnetic flux, generate their magnetic field opposed to the applied external field, causing a shielding effect. As a result, the magnetic response of the ferromagnet is further distorted, and the shape and area of the hysteresis loop change, indicating an increase in reversal magnetization losses. Such changes are particularly significant under high-frequency influences. They are critical for understanding the behaviour of materials in alternating fields, for example, in transformer cores, microwave magnetic systems, or electromagnetic separators.

At the same time, when considering electrically conductive bodies in alternating magnetic fields, it is essential to account for the effect of eddy currents induced by electromagnetic induction. According to Lenz's law, these currents generate their own magnetic field, which is directed opposite the externally applied magnetic field. As a result, partial shielding occurs: the magnetic field generated by the eddy currents hinders the penetration of external field into the interior of the material. The magnetic field induction generated by eddy currents is zero at the body surface. However, its intensity increases toward the body centre, which causes a non-uniform distribution of the resulting induction across the ferromagnet section. This effect is most pronounced at high frequencies of the alternating magnetic field [28]. Under this condition, the magnetic field is concentrated primarily in the near-surface layers, with minimal penetration into the interior of the material. This leads to a reduction in the effective magnetic permeability of the conductive ferromagnetic layer located along the force lines in the external magnetic field. A decrease in permeability means that the material loses its ability to effectively concentrate magnetic flux, which is a critical factor in the design and use of magnetic components in high-frequency devices such as transformers, impedance coils, or magnetic separators. As a result, eddy current losses also increase, reducing the system overall energy efficiency.

Thus, magnetic separation is the primary method for the beneficiation of magnetite ores. The recovery of valuable component becomes possible due to magnetite particles' high magnetic susceptibility and the lack of magnetic properties in non-metallic particles. At the same time, ferromagnetic particles possess a fairly strong remanent magnetization. Even after leaving the high-gradient magnetic field zone, magnetite particles "retain" the field, resulting in secondary magnetic fields generated by individual particles. As a result, magnetic interactions occur between the particles, with individual particles forming floccules - elongated and spatially oriented "strands" that can exceed the size of a single magnetite particle by a factor of 100 or more. The formation of floccules hinders further processing of magnetite ores [29], [30]. Firstly, under the influence of the induced secondary magnetic field, the movement of ferromagnetic particles toward each other occurs in an avalanche-like manner. This leads to the inclusion of non-metallic particles within the floccule body and a decrease in iron-ore concentrate quality. Therefore, obtaining pure concentrates using magnetic separation alone is theoretically impossible. Secondly, after the separation of particles in the magnetic field, the granulometric composition of the separation products changes. This leads to a decrease in the efficiency of subsequent size classification and an increased load on the grinding equipment, as a particular portion of the prepared size fraction is continuously returned to the mill, significantly growing the circulating load [31]. As a result of flocculation, the rheological properties of the ferromagnetic suspension deteriorate. The viscosity of the separating medium decreases, leading to changes in the process parameters during the dense medium separation. The theoretically possible beneficiation performance of magnetite ores is only possible by minimizing particle-to-particle interactions caused by secondary fields. This condition can be met only due to complete demagnetization [32].

According to theoretical views on the magnetism of rocks, demagnetization should occur in an alternating magnetic field with a decreasing intensity amplitude [33]. The first laboratory prototypes of high-frequency demagnetizing devices operated at frequencies of up to 500 Hz [34]. However, the lack of reliable electronic components became a significant obstacle to producing industrial models. Demagnetizing devices with an alternating magnetic field at 50 Hz are used in beneficiation processes [35].

The operating principle of demagnetizing devices is as follows. Mineral particles of fine sizes are transported as a suspension during the processing. The transport channel of the device is designed as a pipe made of non-magnetic material, sized for a specific pulp flow rate. An electrical winding is placed around the pipe. It is divided into sections according to the magnetic field amplitude: the number of turns in each subsequent section gradually decreases, reducing its diameter. The pipe can be made of metal with high specific electrical resistivity to reduce eddy currents or of plastic. Due to this design, the magnetic field intensity gradually decreeses from a value that ensures particle saturation to zero. This enables the demagnetization of mineral particles in the pulp. It should be noted that the effect of a low-frequency alternating magnetic field on a ferromagnetic pulp does not result in complete demagnetization of ferromagnetic particles, since they manage to orient themselves with the axis of easy magnetization along the vector of the external magnetic field. Some improvement in the rheological properties of the ferromagnetic suspension that has passed through the demagnetizing device can be explained by the mechanical destruction of floccules to sizes determined by the residual magnetization of the ferromagnetic particles [36].

The main condition for demagnetizing a ferromagnetic body is stabilizing its position in space relative to the vector of the external alternating magnetic field [37]. It is not feasible to fix the position of all individual particles in the suspension by mechanical means. No matter how small the material body is, it possesses mechanical inertia. Even magnetic domains have magnetic inertia, and at sufficiently high frequencies, they do not have time to respond to changes in the magnetic field. Mechanical inertia is proportional to the particle mass, so the polarity of the magnetic field must be reversed quickly enough that the particle does not have time to change its position. Accordingly, the smaller the particle size is, the higher the frequency of reversal magnetization should be. At the same time, the intensity of the demagnetizing field should exceed the magnetic saturation of the ferromagnetic material. Therefore, to achieve complete demagnetization of fine-dispersed magnetite suspensions, the demagnetizing device should have a high intensity and operate at a high alternating frequency of the magnetic field. Achieving such parameters is a complex scientific and practical task that requires justification of the device design, calculation of optimal operating modes, as well as consideration of the electromagnetic properties of the medium and energy consumption to ensure stable and efficient operation under industrial conditions. It should be noted that both theoretical and experimental research results confirm that the use of high-frequency demagnetizing devices significantly improves the efficiency of magnetite ore beneficiation, brings technological indicators closer to theoretically possible values, enhances the quality of subsequent material classification, and reduces the load on grinding equipment [38]-[40].

Therefore, the research purpose is to substantiate the parameters of the high-frequency demagnetization technology for magnetite suspensions, taking into account the revealed patterns of changes in the electrical resistivity of circulating water and changes in magnetic field induction depending on the concentration of dissolved salts. To achieve the stated purpose, the authors of the work tackled the following interrelated tasks:

– to determine the relationship between the change in electrical resistivity of circulating water and the salt content;

– to establish the dependence of magnetic field induction along the solenoid axis on the distance from its edge and the surrounding medium;

– to study the sedimentation kinetics of magnetite suspension after its treatment with a high-frequency alternating electromagnetic field.

2. Research methods

The objects of this research are the circulating water used in the plant water supply system and the magnetite concentrate, which is the final product of magnetic separation at the mining and processing plant PJSC Northern Iron Ore Enrichment Works (PJSC NORTHERN GOK). PJSC NORTHERN GOK is one of the largest mining and processing companies in Europe that prepares raw materials for the metallurgical industry. This plant is part of the METINVEST HOLDING, LLC. METINVEST HOLDING product line of iron ore pellets for blast furnace production includes unfluxed pellets produced by PJSC NORTHERN GOK with a basicity of 0.12 and an iron content of 62.5%, as well as fluxed pellets with a basicity of 0.5 and an iron content of 60-61.9%. The iron ore agglomerate from PJSC NORTHERN GOK is represented by unfluxed agglomerate with an iron content of 62% and fluxed agglomerate with an iron content of 50-57% [41].

Laboratory studies were conducted in two consecutive stages. At the first stage, the electrical conductivity of the recirculating water from the beneficiation plant was determined. The second stage involved assessing the degree of demagnetization of magnetite particles by studying the sedimentation kinetics of both magnetized and demagnetized magnetite suspensions. The conductometric method was used to determine the dependencies of change in the electrical conductivity of the circulating water from the PJSC NORTHERN GOK beneficiation plant. This method allows measurements under alternating current conditions and varying mineralization by reducing polarization effects on the electrodes. According to the schematic diagram of the laboratory setup (Fig. 1), the conductometric cell consists of two electrodes made of stainless steel positioned in a glass container with a salt solution. This cell was connected to an alternating current source through a measuring resistor, which ensured control and stability of the current load during the experiments. The measurements were conducted with alternating current frequencies ranging from 25 to 75 kHz between stainless steel electrodes with an area of 2 cm^2 and a distance of 2 cm between them. The specific density of the alternating current did not exceed 13 A/dm^2, preventing electrolysis of the water.

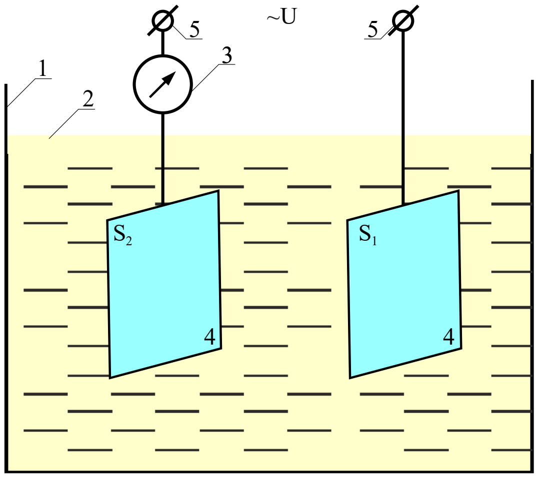

Figure 1. The schematic diagram of the laboratory setup for studying the electrical conductivity of the circulating water from the beneficiation plant: 1 – calibrated glass cylinder; 2 – circulating water; 3 – A-meter; 4 – electrodes; 5 – terminals for connecting the alternating current source

The demagnetization ratio of magnetite particles was determined based on the study of the sedimentation kinetics of magnetized and demagnetized magnetite suspensions. Sedimentation was carried out in a calibrated glass cylinder with a volume of 1000 cm³ and a height of 40 cm. The height of the settled sediment layer was measured at regular time intervals. During the sedimentation analysis, a suspension with a volumetric concentration of 10% magnetite was poured into the mentioned cylinder. Magnetite concentrate from PJSC NORTHERN GOK after the fourth grinding stage, with a total iron content of Fe^{tot} of 66.1% was used for the experiments. The content of particles smaller than 40 μm in this product accounted for 92%. During the experiments, the cylinder was closed, and the suspension was thoroughly mixed to ensure a uniform distribution of particles throughout the volume. After placing the sample on a horizontal surface, a video recording of the sedimentation process was conducted. Frame-by-frame analysis was then used to determine the temporal dynamics of sediment height changes.

To demagnetize magnetite particles, a special device, a solenoid, was used, which, together with a capacitor, forms an oscillatory circuit (Fig. 2). In this circuit, damped high-frequency electromagnetic oscillations are periodically generated by supplying current pulses. As a result, an alternating magnetic field is created in the solenoid, the amplitude of the magnetic induction of which initially exceeds the remanent magnetization of the ferromagnetic particles and, over time, decreases to zero. A magnetite particle residence time in the solenoid operating space is determined proportionally to its length and inversely to the suspension flow rate. The period of excitation pulses was selected in such a way as to ensure that the time for the magnetite particle passing through the solenoid operating space corresponded to the timing of the pulses. This ensured that each particle was exposed to the demagnetizing electromagnetic impulse at least twice during its residence within the solenoid operating space. Such a mode effectively reduces the remanent magnetization of the particles due to repeated action of the alternating magnetic field, the amplitude of which at the beginning exceeds the remanent induction of the ferromagnetic material [42].

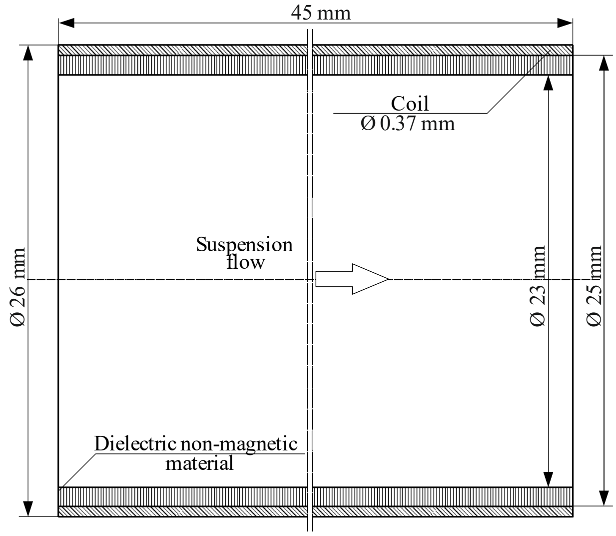

Figure 2. The schematic diagram of the laboratory high-frequency demagnetizing device

Providing that the demagnetization device is intended for use at beneficiation plants where suspensions are transported through pipelines with an internal diameter of 200 mm, the solenoid design should consider these technical features. In particular, the solenoid outer diameter exceeds the pipe internal diameter by twice the thickness of its wall, ensuring hermetic sealing and compatibility with the existing pulp delivery system. The pipe on which the solenoid is wound is non-conductive and non-magnetic. According to the technical design, the length of the solenoid is less than twice the pipeline diameter. Such a solenoid is considered short, and its magnetic field is non-uniform in both axial and radial directions. Under these conditions, the weakest magnetic field induction occurs radially along the solenoid axis and axially at its edges. Therefore, the operating space is defined based on the magnetic induction along the solenoid axis, which should be equal to or greater than the remanent magnetization of magnetite. The flow of the magnetite suspension in the circulating water of the beneficiation plant passes through the solenoid. Thus, the alternating electromagnetic field is generated by the current in the solenoid windings and propagates from them toward the centre through the ferromagnetic, electrically conductive medium, where energy dissipation occurs. As a result, the field dampens, and the amplitude of its magnetic component decreases.

The circulating water used at beneficiation plants is typically characterized by an elevated content of hardness salts (ranging from 0.5 to 25 kg/m³), which significantly increases its electrical conductivity. Magnetite is transported in a suspension, as its classification and beneficiation occur in an aqueous medium. Since the circulating water is a component of the magnetite suspension, it is evident that its properties will influence on the electromagnetic field dissipation. The average density of the magnetite suspension is 1450-1500 kg/m³. Accordingly, the average volumetric concentration of solid particles amounts to 10%. Therefore, the magnetic permeability of the fine-dispersed magnetite suspension can be expressed as 0,1 μ, assuming the magnetite particles are uniformly distributed throughout the volume. Under these conditions, the medium can be considered homogeneous, and its relative magnetic permeability will be proportional to the volumetric concentration.

3. Results and discussion

Within the first stage of the research, it has been determined that the electrical resistivity of the circulating water varies depending on its mineralization level, which is described by the dependencies shown in Figure 3.

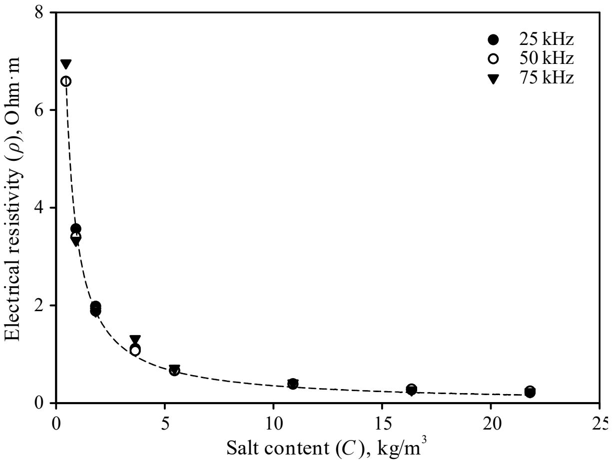

Figure 3. Dependence of the change in electrical resistivity of circulating water on salt content

As can be seen from the graph shown in Figure 3, the active component of the electrical resistivity of the circulating water practically does not depend on the alternating current frequency within the studied range. This indicates that the dominant contribution to the total resistance is made by ionic conductivity, which is only weakly sensitive to frequency changes within the specified limits. Thus, frequency characteristics do not significantly impact the measurement results in this case. In this regard, for each salt content value in the water, it is advisable to average the measured values of the electrical resistivity and use them to plot an approximating dependence. The obtained averaged values are well described by a function of the form:

$$\rho = \frac{ab}{(b+C)}, \quad (1)$$

where:

ρ – electrical resistivity, Ohm·m;

C – salt content;

a, b – empirical coefficients (43,61; 0,08).

Substituting this function into the formula for determining the dissipation coefficient of the electromagnetic field in the suspension, based on the phenomenon known as the "skin effect" [43], the latter takes the form:

$$\beta = \sqrt{\frac{\pi \mu_r \mu_0 f (b+C)}{ab}}, \quad (2)$$

where:

μ_r – the relative magnetic permeability of the material;

μ_0 – magnetic constant ($4\,\pi \cdot 10^{-7}$ N/A^2);

f – electromagnetic field frequency, kHz.

Taking into account the electromagnetic field energy dissipation in the fine-dispersed magnetite suspension, the amplitude value of the magnetic field induction, in our case, takes the following form:

$$B = B_0 \cdot e^{-R\sqrt{\frac{\pi \mu_r \mu_0 f (b+C)}{ab}}}, \quad (3)$$

where:

B_0 – amplitude of induction without energy dissipation;

R – radius of the demagnetizing solenoid, m.

Thus, Equation (3) for determining the magnetic field induction at an arbitrary point along the solenoid axis, taking into account its dissipation in the fine-dispersed magnetite suspension, will have the following form:

$$B_x = \frac{\left(1+(\mu-1)\cdot C_v\right)\cdot \mu_0 \cdot N \cdot I \cdot e^{-R\sqrt{\frac{\pi \mu_r \mu_0 f (b+C)}{ab}}}}{L} \times \left(\cos\alpha_1 - \cos\alpha_2\right), \quad (4)$$

where:

N – number of solenoid turns, pcs.;

I – current intensity, A;

L – length of the solenoid, m;

x – position of the investigated point on the solenoid axis, m;

$\cos\alpha_1 = \frac{x}{\sqrt{R^2+x^2}}$, $\cos\alpha_2 = \frac{L-x}{\sqrt{R^2+(L-x)^2}}$ – angles between the axis and the lines drawn from the point x to the edges of the solenoid, deg.

Based on the initial data for operating conditions of the PJSC NORTHERN GOK beneficiation plant ($R = 0.1$ m, $L = 0.2$ m; $\mu = 15$, C_v – volumetric concentration of magnetite in the suspension (5; 10%); $N = 10$ pcs.; $I = 2000$ A; $\rho = 0.2$; 6.0 Ohm·m; $f = 50$ kHz), dependencies were obtained characterizing the change in the magnetic field induction along the solenoid axis depending on the distance from its edge and the surrounding medium (Fig. 4).

The analysis of the presented research results (Fig. 4) indicates that the lowest amplitude value of magnetic induction of 0.8 T corresponds to the solenoid placed in the air (Fig. 4, curve *3*). In the presence of ferromagnetic magnetite particles within the solenoid as part of the suspension at a volumetric concentration of 10%, the magnetic permeability of the medium increases, resulting in a rise in magnetic induction to 0.13 T (Fig. 4, curve *1*). The electrical conductivity of the salt solution in the suspension causes the dissipation of the alternating electromagnetic field energy, which leads to a decrease in induction to 0.12 T (Fig. 4, curve *2*). The remanent magnetization of magnetite from the PJSC NORTHERN GOK is approximately 0.1 T. In this case, as shown in Figure 4, the operating demagnetization space in the solenoid will be located at a distance of 0.044 m from its edges, meaning it will be shorter by 0.088 m and measure 0.011 m. From a design standpoint, applying excitation current pulses to the solenoid at 100 Hz is advisable, with a pulse period of 0.01 s. At the same time, the maximum suspension flow velocity is 11.2 m/s. To ensure complete demagnetization of the magnetite, it should be demagnetized at least twice within the solenoid operating space. This provides a maximum suspension flow velocity of 5.6 m/s.

It should be noted that, to verify the obtained results regarding the change in magnetic field induction, additional studies were conducted aimed at examining the kinetics of sedimentation of the magnetite suspension after its treatment with a high-frequency alternating electromagnetic field. In the case of floccules destruction and the release of individual magnetite particles, the suspension sedimentation rate decreases significantly.

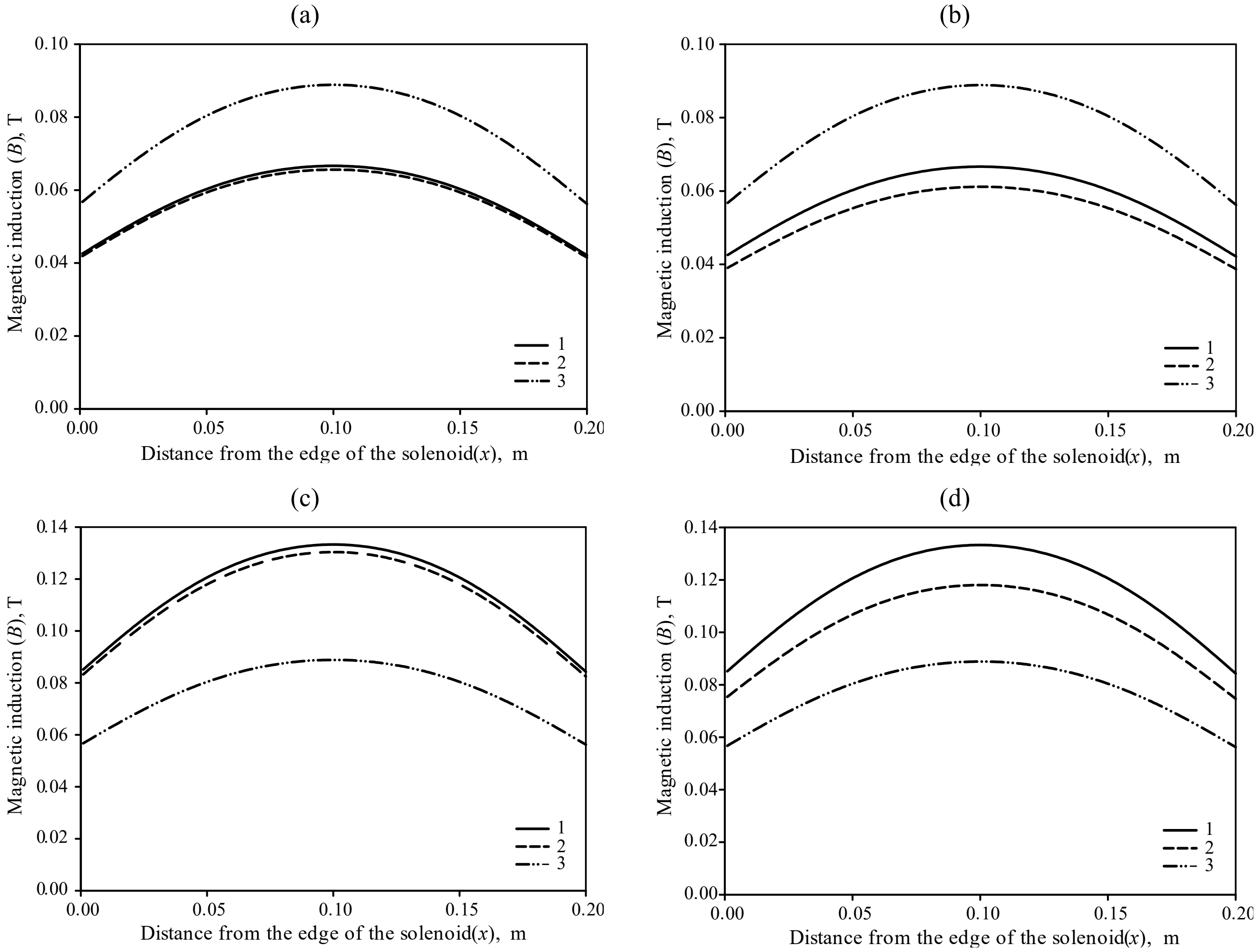

Figure 4. Dependence of magnetic field induction along the solenoid axis on the distance from its edge and the surrounding medium: 1 – with the suspension, without taking dissipation into account; 2 – with the suspension, taking dissipation into account; 3 – in the air;: (a) ρ = 6.0 Ohm·m; C_v = 5%; (b) ρ = 0.2 Ohm·m; C_v = 5%; (c) ρ = 6.0 Ohm·m; C_v = 10%; (d) ρ = 0.2 Ohm·m; C_v = 10%

This is due to the absence of magnetic interaction between the particles, which typically promotes their aggregation into larger floccules. Without flocculation, the dispersed system loses its ability to form aggregates, and each particle settles individually under the action of gravity. It is accompanied by a reduction in the effective mass of the sediment and a slowdown in the sedimentation process. The sedimentation rate of an individual magnetite particle measuring 20-40 µm will be significantly lower than that of a floccule measuring 200 µm. The results of the conducted studies are shown in Figure 5. The sedimentation rate is defined as the ratio of the clarified layer height to the time required for its formation.

The analysis of the data presented in Figure 5 shows that the sedimentation rate of the demagnetized suspension is 3.1 times lower compared to the magnetized one. Such a significant decrease in sedimentation rate indicates effective demagnetization of the magnetite particles, leading to the destruction of interparticle magnetic interactions and floccules. As a result, the particles settle individually without forming aggregates, which explains the reduced sedimentation rate. Therefore, the experimental results confirm the achievement of almost complete demagnetization of the suspension under the influence of the alternating electromagnetic field.

The results of the conducted research indicate that the identified peculiarities of the mechanism for electromagnetic field energy dissipation are of key importance for optimizing the design of the demagnetization device.

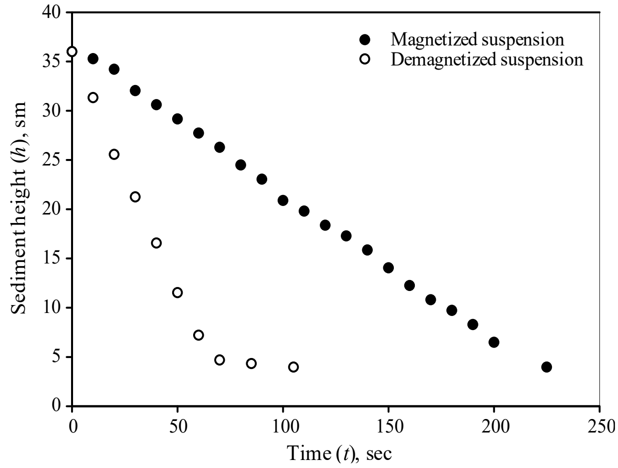

Figure 5. Dependence of the sediment height (h) of magnetized and demagnetized magnetite suspensions on time (t)

In particular, the identified patterns of energy distribution and absorption in the operating medium allow for a more precise determination of the optimal design parameters of the device, taking into account both demagnetization efficiency and the specified technological operating conditions. This, in turn, contributes to increased process productivity, reduced energy consumption, and stable operation of the device under the industrial conditions of beneficiation plants.

Moreover, obtaining pure and ultra-pure magnetite concentrate is an important scientific and practical task, since using such raw materials enables the direct reduction of Fe to obtain powdered iron and produce ultra-pure alloys.

4. Conclusions

Demagnetization of magnetite suspensions is a crucial process in preparing raw materials for mineral processing, as the remanent magnetization of particles significantly reduces the efficiency of subsequent separation by causing aggregation and flocculation. An analysis of the interaction mechanisms between magnetic fields and ferromagnetic particles has shown that using a high-frequency alternating electromagnetic field with gradually decreasing amplitude is the most effective method for achieving almost complete demagnetization of finely dispersed magnetite pulp.

The influence of a high-frequency electromagnetic field ensures the destruction of floccules, restoration of suspension homogeneity, and reduction of interparticle interaction intensity, which is confirmed by the decreased sedimentation rate of demagnetized particles. Using such demagnetizing devices enables improved classification accuracy, reduced energy losses in separation systems, decreased load on grinding equipment, and brings beneficiation performance indicators closer to theoretically possible levels. Therefore, implementing high-frequency demagnetization technology represents a promising approach for enhancing the efficiency of magnetite ore processing.

As a result of the conducted research, a correlation has been revealed between the electrical resistivity of circulating water and its level of mineralization. Specifically, it has been found that electrical resistivity varies within the range of 0.16 to 6.67 $\Omega \cdot m$ as mineralization changes from 0.45 kg/m^3 to 21.8 kg/m^3. The highest electrical resistivity values are observed at the lowest concentrations of dissolved salts, which is explained by the reduced number of ions capable of conducting an electric current. Accordingly, as mineralization increases, the ion concentration in the solution rises, leading to a decrease in the resistivity of circulating water due to increased electrical conductivity. Moreover, changing the alternating current frequency from 25 to 75 kHz does not affect the resistivity value.

It has also been found that the presence of magnetite particles within the solenoid operating space contributes to an increase in magnetic field induction due to significant enhancement of these particles to the medium magnetic permeability. Their effect prevails over the effect of the alternating electromagnetic field dissipation, resulting in a strengthened magnetic influence within the solenoid operating space. It has been determined that the presence in the solenoid of magnetite particles in the suspension in the amount of 10% increases the magnetic permeability of the medium to 0.13 T. At the same time, the sedimentation rate of the demagnetized suspension is 3.1 times lower compared to the magnetized one.

Author contributions

Conceptualization: IM, OB2; Data curation: OB1, OB2; Formal analysis: IM, OD; Funding acquisition: OA; Investigation: OB1, OB2; Methodology: IM, OB2; Project administration: IM, OD; Software: OB2; Supervision: IM; Validation: IM, OB2; Visualization: OB1, OD, OA; Writing – original draft: OB1, IM, OB2; Writing – review & editing: OD, OA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Високочастотне розмагнічування магнетитових суспензій

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Мета. Обгрунтування параметрів технології високочастотного розмагнічування магнетитових суспензій з урахуванням встановлених закономірностей зміни питомого електричного опору оборотної води та зміни індукції магнітного поля від концентрації розчинених солей.

Методика. Зміна показників електропровідності оборотної води збагачувальної фабрики, що входить до складу магнетитової суспензії, досліджувалась в лабораторних умовах кондуктометричним методом при змінному струмі різних частот Величина ступеню розмагнічування магнетитових частинок встановлювалась на основі дослідження кінетики седиментації намагніченої та розмагніченої суспензії магнетиту. Для розмагнічування магнетитових частинок використовували спеціальний пристрій, що представляє собою соленоїд, який разом із ємністю утворює коливальний контур у якому періодично генеруються затухаючі високочастотні електромагнітні коливання шляхом подачі імпульсів струму.

Результати. Розкрито аспекти механізму розповсюдження високочастотного електромагнітного поля всередині магнетитової суспензії з урахуванням коефіцієнту затухання енергії поля та впливу технологічних параметрів суспензії (питомий електричний опір оборотної води, концентрація твердої фази) на характеристики електромагнітного поля. Виявлено взаємозв'язок концентрації твердого магнетиту в суспензії та коефіцієнт затухання електромагнітного поля. У результаті визначення кінетики седиментації виявлено, що швидкість осадження розмагніченої магнетитової суспензії є нижчою порівняно з намагніченою.

Наукова новизна. Отримано залежності зміни питомого електричного опору оборотної води збагачувальної фабрики від вмісту солей у ній та зміни індукції магнітного поля на осі соленоїда від відстані до його краю та оточуючого середовища. Встановлено, що для забезпечення повного розмагнічування магнетиту, його необхідно розмагнічувати щонайменше двічі в робочій зоні соленоїда, що забезпечує максимальну швидкість потоку суспензії 5.6 м/с, при цьому швидкість седиментації розмагніченої суспензії зменшується в 3.1 рази порівняно з намагніченою, що свідчить про ефективність розмагнічування та руйнування міжчастинкових магнітних взаємодій.

Практична значимість. Дослідження можуть слугувати базою для встановлення раціональних параметрів при проєктуванні високочастотних розмагнічувальних апаратів, застосування яких дозволяє підвищити показники збагачення магнетитових руд та наблизити їх до теоретично можливих, підвищити ефективність подальшої класифікації та знизити навантаження на подрібнювальне обладнання.

Ключові слова: *магнетит, кондуктометричний метод, розмагнічування, суспензія, питомий опір, дисипація*

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