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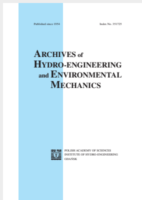

Biotechnology of Underground Waters Treatment with Ferrobacteria Under the Influence of Constant Magnetic Field

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Abstract. In the modern global field of underground water treatment, the technology of biological iron removal is gaining more and more recognition, as it has a number of significant advantages compared to traditional ones, namely: increased rates of Fe(II) oxidation, filtration, as well as a large dirt capacity of the filter filling. Therefore, the search for methods to activate cellular metabolic processes has practical implications. One of the possible ways of such activation is by using the effect of a constant magnetic field (CMF) on communities of ferrobacteria attached to the contact loading of bioabsorbents made of synthetic material. Based on the results of the research, it has been established that the CMF with an induction value of 5–10 mT is the most favorable for the development of ferrobacteria colonies, while the induction of 130–150 mT, on the contrary, inhibits their development. There has been studied the effect of CMF with the power of 10–15 mT on the efficiency of combined processes of treatment from dissolved organic compounds and Fe(II). The results of comparative studies on the effectiveness of various technological schemes are presented. It was found that with the use of CMF with a magnetic induction of 5–10 mT, the effect of iron removal increases by 20%. There has been developed biotechnology for treating weak acid (pH 6.3–6.5), iron-containing (Fe^{2+} 6–8 mg/dm^3) underground waters which is based on the combinatorics of physical (aeration, influence of constant magnetic field) and biochemical (use of ferrobacteria consortia) methods. The main technological parameters of the process: filtration rate for the bioreactor 7–10 m/h, for filters 6–8 m/h; duration of filter cycles for the bioreactor is 2–3 weeks; for filters 44–48 hours have been determined. The theoretical aspects of the impact of CMF on the processes of biochemical treatment of underground water have been substantiated.

Key words: underground water, ferrobacteria, biological method of iron removal, bioreactor, constant magnetic field

1. Introduction

Modern underground waters are a complex multicomponent system, which contains, along with cations, anions, dissolved organic substances, gases, and products of anthropogenic pollution, a microbiological component. Peculiarities of its environment: oligotrophicity, constant temperature regime and high pressure, minimal concentration or almost absence of dissolved oxygen and, conversely, high concentrations of dissolved gases (carbon dioxide (IV) and hydrogen sulfide), lack of sunlight, they all create a unique ecological niche for microorganisms (Goldscheider et al 2006).

Depending on the values of water quality (salinity, pH, the presence of Fe^{2+} Mn^{2+} cations, dissolved oxygen, organic substances, anthropogenic pollution), microorganisms selectively colonize certain aquifers, creating unique bacterial communities unlike other terrestrial ecosystems (Lee et al 2018, Sha et al 2023).

Ferrobacteria are the most widespread in underground aquifers (Cullimore and McCann 1974, Seppänen 1991, Mouchet 1992). In particular, the work (Cullimore and McCann 1978) emphasized their presence in underground waters of 150 countries of the world. Thus, in the underground waters of the Australian states of Victoria and Queensland, bacteria of the genus *Gallionella* prevail; in most Canadian provinces – *Gallionella*, *Crenothrix*, *Leptothrix*, *Clonothrix*, *Sphaerotilus* and *Siderocapsa*; widespread bacteria in Calcutta area: *Clonothrix*; in Norway – *Gallionella*; Sweden – *Gallionella*, *Crenothrix*, *Leptothrix*; the United Kingdom – *Gallionella*, *Leptothrix*, *Crenothrix*.

The distribution ranges of certain genera of ferrobacteria depend on the quality parameters of natural waters, Table 1–2.

Table 1. Comparison of conditions and features of *Gallionella*, *Leptothrix* and *Sphaerotilus* (Ankrah and Søgaard 2009)

Genus	*Gallionella*	*Leptrothrix*	*Sphaerotilus*
Food type	Chemolithoautotrophic	Chemoheterotrophic	Chemoorganotroughs
Energy/Carbon Source	Carbon dioxide in form of principally HCO_{3-}	Sugars, organic acids and glycerol	Carbon sources like sugars, organic acid
Type of iron produced	Ferrihydrite	Ferrihydrite	Ferrihydrite
Living conditions	Anaerobic and microaerophilic	Slightly aerobic to aerobic	Anoxic and aerobic
	Oxygen content: 0.1 – mg/l	Oxygen content: 1 mg/l	Oxygen content: < 0.1 mg/l – full saturation oxygen saturation
	Temp: 8–16°C	Temp: 10–40°C	Temp: 10–40°C
	Eh (−300) mV	Eh not specified	Eh not specified
	Fe^{2+} 2–25 mg/l	Fe^{2+} content: not specified	Fe^{2+} content: not necessary
	pH 6–7.6	pH 7.5	pH: 5.4–9

The use of underground iron-containing waters in the water supply systems of settlements and industrial enterprises, without prior treatment, was always accompanied by the bacterial development of ferrobacteria inside them. As a result, the formation of ferrohydrite growths was observed on the walls of wells, pump impellers, internal surfaces of pipelines with their subsequent colmotage and biocorrosion, which led to the deterioration of water quality. In the middle of the last century, an idea occurred to use the properties of ferrobacteria for the benefit of underground waters treatment processes.

Table 2. Range of habitats in which iron bacteria occur and their ability to oxidize reduced iron and manganese salts (Cullimore and McCann1978)

Genus	Habitat					Oxidizes		Non-colloidal metal encrusted on cells
		Mud sediments						
	Soil	Fresh water	Bogs	In lakes and rivers	Well water	Fe only	Fe and/or Mn	
Leptothrix	–	+	–	+	+	–	+	+
Crenothrix	–	+	–	–	+	–	+	+
Clonothrix	–	+	–	–	+	–	+	+
Gallionella	+	+	+	+	+	+	–	+
Metallogenium	+	+	–	+	–	–	+	+
Thiobacillus ferrooxidans	+	+	+	+	+	+	–	+/–
Siderocapsa	–	+	–	–	+	–	+	+
Siderococcus	–	–	–	+	–	+	–	+/–

The first data on the possibility of using iron bacteria at water treatment plants were given in 1952 (Tanimoto 1959), who described the process of Fe(II) removal on slow sand filters in Tadotsuco, Kagawa. The first modern systems of biological iron removal from underground waters in Europe, using rapid sand filters, were developed and implemented in Alsace in the 1980s of the 20th century (Hettler 1982). Later, this method was implemented at sewage treatment plants in more than 100 settlements with a capacity of 20 to 2200 m^3/h. The first biological iron removal plants in the UK and the USA were installed in 1987 and 1996 respectively (Mouchet 1995).

In Ukraine, the works on research and implementation of the biological method of iron removal began in the 70s of the 20th century at the Department of Water Supply and Drilling of the UIWME (NUWEE) under the guidance of Professor M. A. Safonov (Safonov and Rusak 1984).

The innovativeness of the method lies in several directions at a time:

1. Increased rate of oxidation of Fe^{2+} compounds by communities of ferrobacteria. Thus, in the work (Søgaard et al 2001) it was indicated that the rate of biotic Fe precipitation/oxidation to be about 1000 times faster than previously found for abiotic physicochemical oxidation/precipitation.
2. High rates of biogenic oxidation lead to the possibility of increasing the filtration rate to 10–30 m/h (Mouchet 1995, Søgaard et al 2001, Casey 2009, Kvartenko et al 2018, Kvartenko 2023).
3. The use of the biological method allows increasing the dirt capacity of the filter loading by 4–5 times (Mouchet 1992), reducing the frequency of washing, which leads to electricity and volumes of wash water saving (Kvartenko et al 2018).

The aim of the study is the improvement of the existing technology of biological deironing of underground waters by making use of the influence of constant magnetic field on communities of ferrobacteria attached to the contact loading of bioabsorbents made of synthetic material.

The hypothesis is well known postulates regarding the possibility of influence of magnetic fields on the life processes of microorganisms (Beretta et al 2019). The influence of magnetic lines of force is capable of both boosting and reducing the activity of the cells of microorganisms, which, in our case, has application-oriented implications in the field of underground waters treatment biotechnology.

The objects of the research are complex physical and biological processes of treatment of multi-component iron-containing underground waters by consortia of bacteria of the genera *Gallionella* and *Leptothrix*.

2. Materials and Methods

2.1. Methods of Research

Fe^{2+} ions concentrations were measured according to MVV 081/12-0175-05 by the colorimetric method with potassium rhodanide on a KFC-3 photoelectrocolorimeter with a wavelength of 490 nm. Determination of pH values was carried out on a universal EV-74 ionometer using, respectively, glass /ESL-43-07/ and platinum /EPZ-1/ electrodes at a constant temperature of 25.0 ± 0.2°C. The study of the values of permanganate oxidation of natural waters was carried out according to GOST 23268.12-78.

Water samples containing ferrobacteria were taken using special samplers with a brass mesh. Samples of contact material with matrix structures of bio-minerals were taken using Perfiliev stratometer. For the quantitative accounting of ferrobacteria, the ten-fold dilution method was applied using nutrient media that were sterilized at 1 atmosphere for one hour in an autoclave. The cultivation was carried out on Petri dishes.

Physical methods of research. Power characteristics of magnetic fields were determined using a universal teslameter 43205.

Electron microscopy of samples of matrix structures of bio-minerals was carried out using the method of X-ray spectral analysis with the help of a scanning electron microscope (SEM) Quanta 200 (USA). The device was equipped with an X-ray spectrometer for microanalysis (EDAX).

2.2. Research Methodology

The research was conducted in several stages. At the first stage, with the help of a universal teslometer 43205, the power characteristics of magnetic fields with different values of induction from blocks of constant magnets measuring 50×80 mm were determined (Fig. 1).

At the second stage, the influence of constant magnetic field with different induction values on communities of microorganisms that developed in a nutrient medium of the following composition (in g/dm^3) was determined: $(NH_4)_2SO4$ – 0.3; $CaCl_2 \cdot 6H_2O$ – 0.05; $MgSO_4 \cdot 7H_2O$ – 0.1; $NaHCO_3$ – 0.3; phosphate buffer 10% (pH

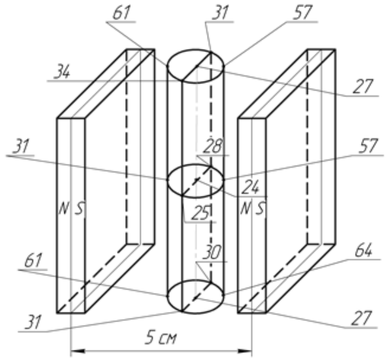

Fig. 1. Scheme of the pilot experimental installation for studying the process of CMF action on communities of microorganisms under conditions of water rotation in the field of power lines. Source: own elaboration

7.0) – 0.1; Hepes buffer (pH 7.0) – 3.0; KNO_3 – 0.3; CH_3COONa – 0.15; vitamins and microelements; distilled water 1 dm^3. The pH of the medium is 6.8.

Samples were taken simultaneously in five measuring glasses volume by 100 ml and were successively subjected to constant magnetic field (CMF) treatment with the induction value, respectively: 1 – 5–15 mT; 2 – 30–50 mT; 3 – 130–150 mT; 4 – 190–290 mT; 5 – without the influence of all the factors listed above (control experiment). The treated water was left in an undisturbed state for 35–40 minutes, after which 1 ml of the sample was taken from each glass and a number of consecutive tenfold dilutions were prepared, from which cultures were carried into a nutrient medium in a Petri dish and then placed for 24 hours in a thermal cabinet with the temperature of 22°C.

At the third stage, in order to study the dynamics of the process of treating natural water from dissolved organic substances and Fe(II) cations by a fixed biocenosis, comparative studies were conducted on two pilot installations which consisted of the biofilter tower made of plexiglass, dimensions 100×100 mm in plan and 500 mm high. The height of the contact loading layer was 300 mm. One of the installations worked in a regular mode, while the other – under the influence of constant magnetic field with the power of 10–15 mT (Fig. 2).

The biofilters of both pilot installations were simultaneously supplied with the same amount of water coming out a constant level tank. An imitation solution of natural water contaminated with easily oxidizable organic impurities (PI 9.5 mg O_2/dm^3) and Fe(II) cations (5.5–6.3 mg/dm^3) was used as source water.

At the fourth stage, the research was carried out on a pilot experimental installation (Fig. 3) installed in the premises of the iron removal station of the urban-type settlement in Rivne region.

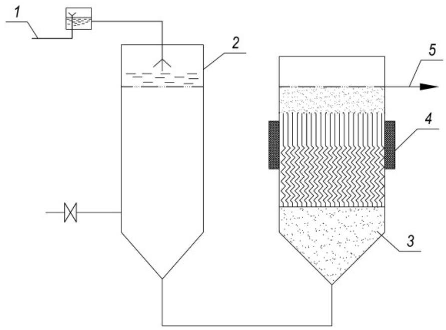

Fig. 2. Scheme of the pilot experimental installation: 1 – coming out water permanent level tank; 2 – air-stripping tower; 3 – biofilter tower; 4 – constant magnets system; 5 – nipple pipe for processed solution.
Source: own elaboration

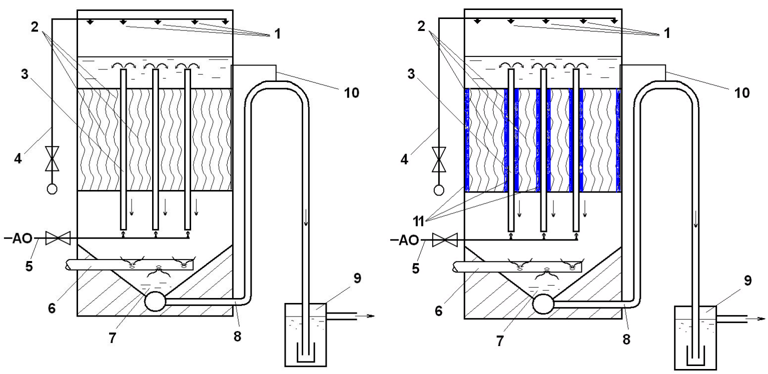

Fig. 3. Left – Bioreactor with KTJT modules; Right – Bioreactor with KTJT modules and the constant magnets system (CMS).
1 – aeration nozzles; 2 – bioabsorbent module; 3 – water-jet airlifts for water recirculation; 4 – pipelines for coming out water supply; 5 – pipelines for compressed air supply; 6 – pipelines for transporting preliminarily treated water to illuminant filter; 7 – sediment section; 8 – washing syphon; 9 – hydraulic lock; 10 – vacuum break pipe; 11 – constant magnets system.
Source: own elaboration

The installation included: a bioreactor with the diameter of 260 mm and 4500 mm high, in the middle part of which there were contact loading modules (2) made of synthetic material – kapron textured jute thread (KTJT) 1200 mm high. The system of three evenly spaced 2000 mm high water-jet airlifts (3) d = 15 mm was used to recirculate oxygenated water. To activate the process of biological iron removal, the system of constant magnet blocks (11) with the induction value of 5–15 mT was used.

The coming out water entered the installation through the pipeline (4) equipped with the system of nozzles (1). The installation was also equipped with compressed air supply pipelines (5), the transport of purified water to the illuminant polystyrene filters (6) and a washing siphon (8). The illuminant filters (two units) was made of a 200 mm steel pipe 2000 mm high. The thickness of the polystyrene filling was 1000 mm with fraction size of 0.63–2.0 mm.

Quality parameters of natural underground waters: hardness 4.6 mmol/dm^3; bicarbonate alkalinity 2.0 mmol/dm^3; permanganate oxidation 6.92 mgO_2/dm^3; Fe^{2+} 6.0–8.0 mg/dm^3; carbon dioxide 80 mg/dm^3; hydrogen sulfide concentration 4.0 mg/dm^3; temperature 8–10°C; pH 6.5–6.8; Eh −700 – (−500) mV.

The principle of the installation operation. The coming out water through the pipeline 4 enters the system of aeration nozzles 1, with the help of which it is sprayed over the surface of the water in the bioreactor resulting in mass exchangung processes, namely partial degassing of dissolved gases (hydrogen sulfide and carbon dioxide) with simultaneous saturation of water with air oxygen. The water, with altered parameters of pH-Eh values, flows down through the contact loading modules 2 with attached ferrobacteria. In order to create optimal conditions for the development of ferrobacteria in the system of modules, the system of water-jet airlifts is used allowing recirculation of the air-water mixture from the lower part of the device into the space above the contact filling medium. By adjusting the flow of compressed air, the creation of optimal conditions for the development of ferrobacteria in terms of dissolved oxygen concentration, pH, and redox potential is achieved.

The nozzle of the bioreactor has a small negative electrokinetic potential (−27 mV), which leads at the beginning to an intensive process of sorption of positively charged Fe^{2+} ions. Over time, the contact loading acquires a positive charge, which contributes to the electrostatic retention of ferrobacteria cells. It is known (Murad et al 1990) that the process of accumulation of ferrum (III) oxides on the surface of bacterial cells is the result of two interrelated processes: accumulation of this metal by cells from solution and their oxidation by the products of *Leptothrix* bacterias metabolism:

$$2Fe^{2+} + H_2O_2 + 2\,H^+ \rightarrow 2Fe^{3+} + 2H_2O$$

As a result of their vital activity, these bacteria create matrix structures of ferrihydrite bio-minerals around themselves ($2.5Fe_2O_3 \times 4.5H_20$) is common, which over time turns into lipidocrocite γ-FeOOH (Angelova et al 2015, Abrajevitch et al 2016). In addition, the formation of magnetite and goethite nanocrystals is observed in matrix structures (Nesterova et al 2003, Kennedy et al 2004, Chana et al 2009).

When a permanent magnetic field is applied from the outside, the biosystem is activated due to the formation inside the nozzle module of a huge number of micromagnets from mineralized capsules that attract oxygen, oxygen radicals, Fe^{2+} ions, as well as covers with active ferrobacteria. Oxygen radicals, which are released in the process of oxidation of ferrum compounds by metabolic products of bacteria of the genus *Leptothrix*, migrate to the poles of nearby micromagnets (artifacts of matrix structures), which are transformed from an inert sediment into active microparticles under the influence of a magnetic field. Oxygen and its radicals are attracted to the surface of such macroparticles that oxidize adsorbed Fe2+ ions. In this system, oxygen, as a true paramagnet, is directed both to magnetized artifacts and to ferrobacteria fixed on their surface, accelerating the processes of enzymatic reactions (Kvartenko and Zhurba 2010).

Having left the bioreactor, the water flows through pipeline 6 to the polystyrene foam filters, where it is finally purified of ferrum compounds.

3. Results and Discussions

3.1. Study of the Effect of Magnetic Fields of Different Induction Values on the Development of Colonies of Microorganisms (2 Stage)

The obtained results demonstrated the largest increase in the colonies of microorganisms in the sample exposed to a constant magnetic field (CMF) with an induction value of 5–10 mT (Fig. 4) – 455 colonies in the third incubation. The count of colonies in the studied samples showed the greatest increase in small and medium-sized colonies (curves 2, 3).

With the force field increase to 25–30 mT, there was observed a gradual inhibition of the development of colonies of microorganisms to 320–350 units. With the further

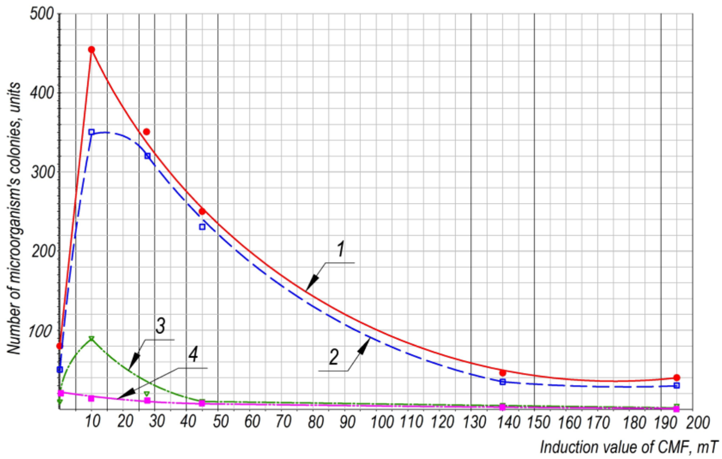

Fig. 4. Dependence of the number of microorganism's colonies in the third incubation on the induction value of CMF: 1 – the total number of colonies; 2 – the number of small colonies; 3 – the number of medium-sized colonies; 4 – the number of large colonies. Source: own results

increase in magnetic induction to 130–150 mT, the development of colonies sharply decreased to 37–50 third incubation colonies.

Conducted research on the residual effect of a magnetic field with a magnetic induction force of 130–150 mT 24 hours after exposure (Fig. 5) showed that the given value of the magnetic field significantly suppresses the growth of colonies of microorganisms of the third incubation in physiological solution in comparison with the reference sample.

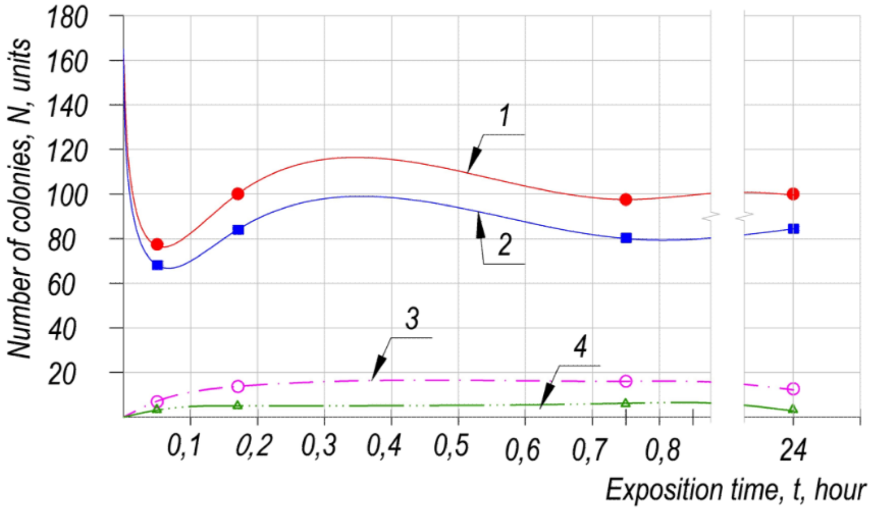

Fig. 5. The residual effect of CMF with the force of 130–150 mT on the growth of the microorganisms colonies 24 hours after the exposure. 1 – the total number of colonies; 2 – the number of small colonies; 3 – the number of medium-sized colonies; 4 – the number of large colonies. Source: own results

3.2. Study of the Effect of Constant Magnetic Field on the Processes of Complex Purification of Underground Waters (Stage 3)

At this stage, the research was conducted with the aim of studying the effect of constant magnetic field with magnetic induction force of 10–15 mT on the effectiveness of combined processes of underground waters treatment. Fig. 6–7 present the results of laboratory studies of the effect of CMF with the force of 10–15 mT on the process of complex treatment of underground waters with Fegen content of 5.5–6.3 mg/dm^3 and permanganate index of 9.5 mg O_2/dm^3.

The application of the effect of CMF of different magnetic induction force on communities of microorganisms allowed increasing the efficiency of water treatment by 15–20% for easily oxidizable organic compounds and up to 30–40% for oxidized

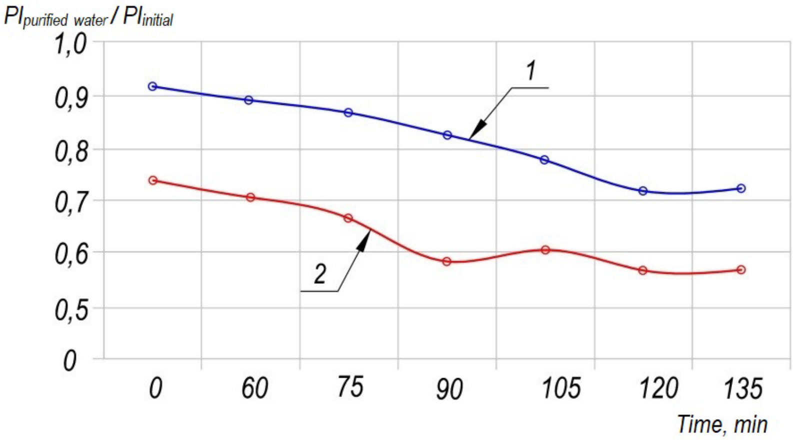

Fig. 6. Dynamics of changes of permanganate index (PI) under different schemes of the coming out water treatment: 1 – after the column of the bioreactor; 2 – after the column of the bioreactor which was under the influence of CMF. Source: own results

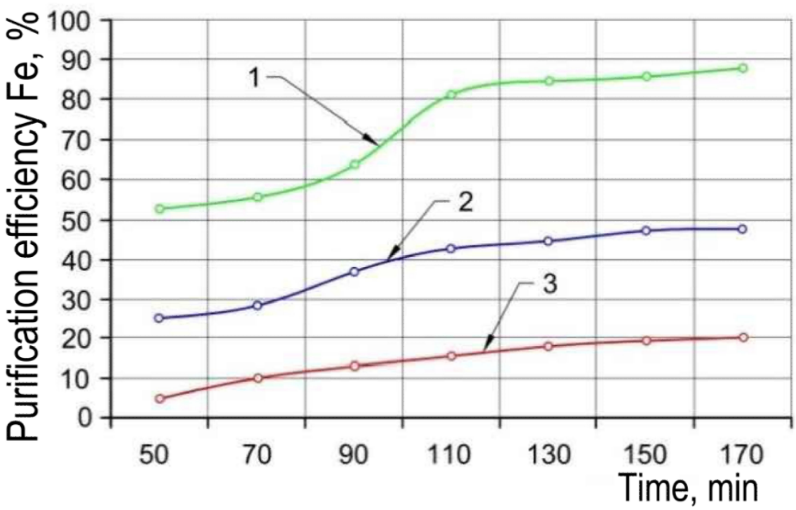

Fig. 7. Dependence of the decrease in the content of Fe^{2+} ions on the installation operation time: 1 – after the column of the bioreactor which was under the influence of CMF; 2 – after the column of the bioreactor; 3 – after the air-stripping tower. Source: own results

iron. The period of adaptation of microorganisms to the environment under the influence of CMF decreased to 30–40 minutes compared to 60–120 minutes under normal conditions.

3.3. The Results of Comparative Researches on the Operation of the Installation on Natural Underground Waters (Stage 4) Which Were Carried Out According to Several Schemes

Scheme I. Simplified aeration – a contact column without a KTJT module – the 1st degree filter with crushed stone filling (with fraction size of 10–20 mm; layer height of 1000 mm) – the 2nd degree filter with sand filling (with fraction size of 0.5–1.5 mm; layer height of 700 mm). The parameters of changes in pH-Eh values of water by stages are given in Table 3.

The effect of purification was the following: on the contact column 8–9%; on the 1st degree filter 43–45%. The main load fell on the 2nd degree filter which cleaned water from ferrum compounds to 0.1–0.3 mg/dm^3 in the first hours of operation. The duration of the filter cycle is 22 hours, the intensity of washing is 17.8 l/cm^2, the duration of washing is from 20 to 40 minutes.

Table 3. Results of changing pH-Eh values while applying simplified aeration

Coming out water		Water after contact column		Water after filter			
				1st degree		2nd degree	
pH	Eh, mV	pH	Eh, mV	pH	Eh, mV	pH	Eh, mV
6.5–6.7	−500 (−600)	6.55–6.7	−440 (−380)	6.67–6.75	−250	6.62–6.68	−80 (+100)

source: own results

After the contact column and filter of the 1st degree, the values of the redox potential indicated the overall reducing nature of the system (Table 3). At such pH-Eh values, Fe(II) compounds are in a stable state.

When aerating water in the contact column with compressed air from pipeline 5, a significant change in pH-Eh values was observed (Table 4).

Table 4. Results of changes in pH-Eh values while bubbling water in the contact column

Coming out water		Water after contact column		Water after filter			
				1st degree		2nd degree	
pH	Eh, mV	pH	Eh, mV	pH	Eh, mV	pH	Eh, mV
6.68–6.7	−700 (−600)	6.8–6.85	−270 (−200)	6.7–6.75	−120 (+50)	6.7	+300 (+450)

source: own results

The efficiency of water treatment in the contact column increased to 18–20%, after the first degree filter to 45–50%, after the second degree filter the concentration of ferrum cations did not exceed 0.1–0.2 mg/dm^3. The duration of the filter cycle is 24 hours. In both variants, it was necessary to use large volumes of wash water to regenerate the filter filling.

Scheme II (Fig. 3 left). Combined aeration system – bioreactor with KTJT modules – polystyrene foam filters. The peculiarities of changes in pH-Eh values when using water-jet airlifts are shown in Table 5. Within the location of the KTJT module owing to the recirculation system the water quality parameters changed from a weak acidic and reducing medium to the borders of the reduction and oxidation zones and neutral pH values, where there are located the areas of bacterial activity of the genera *Leptothrix*, *Gallionella* (Mouchet 1992, Kvartenko 2017).

Table 5. Peculiarities of changes in pH-Eh values while using water-jet airlifts

Coming out water		Water after bioreactor		Water after foam polystyrene filter	
pH	Eh, mV	pH	Eh, mV	pH	Eh, mV
6.3–6.5	−500 (−450)	6.7–6.8	(−50) +100	6.63–6.68	130–180

source: own results

The efficiency of removal of Fe(II) compounds from water at the KTJT module in the first 10–12 hours was 32–38%. After 3–4 days of operation, the capron threads of the nozzle were covered with a thin layer of mucous biofilm. After a week, the surface of the nozzle module acquired a rich dark brown color characteristic of *bio*–FOOH matrix structures. The purification effect constituted 50–57%.

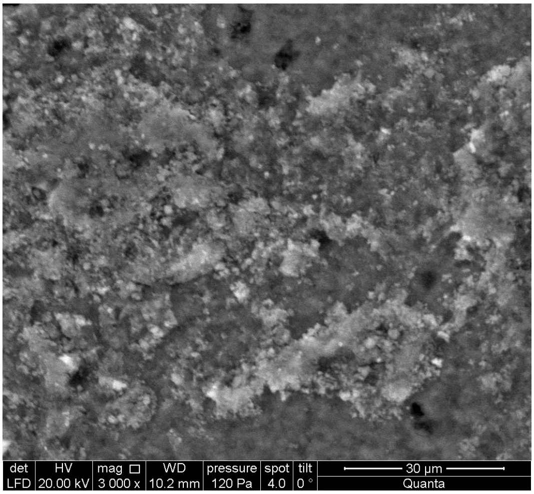

Fig. 8. Microphotograph of the surface of the KTJT area 4 days after the start of operation of the pilot experimental installation 3000×. Source: own study

The filtration rate was maintained within 7–10 m/h. The operation of the KTJT modules lasted 5–7 days instead of 2–3 weeks of those with crushed stone. The visual (Fig. 8) and X-ray spectral (Fig. 9) analysis of the elemental composition of the primary (3–4 days of operation) active catalytic films on the surface of the contact loading, carried out with the help of a scanning electronic microscope, proved the insignificant presence of bacterial associates on the surface of the KTJT modules.

During this period, the processes of biological and chemical oxidation of Fe^{2+} were still competing with each other.

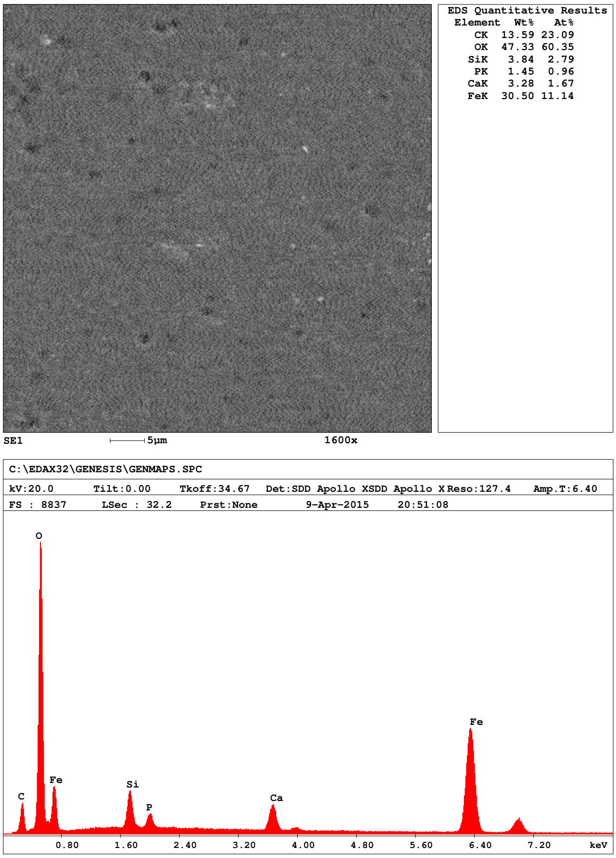

Fig. 9. X-ray spectral analysis of the content of primary active catalytic film on the surface of KTJT module. Source: own study

The duration of the filter cycle for a polystyrene foam filter, at filtration rates of 6–8 m/h, constituted 44–48 hours. Washing lasted for 7–8 minutes. The bioreactor with the KTJT module operated without regeneration for 2–3 weeks under experimental conditions. The efficiency of purification prior to regeneration reached 80–90%. Such a high purification effect is associated with the gradual accumulation of a significant number of ferrobacteria with matrix structures on the surface of the kapron threads of the module and in their interpore space, which was confirmed by the study of washing water samples (Fig. 10).

The major volume consisted of covers in the form of a double spiral (Fig. 11), characteristic signs of the vital activity of *Gallionella* bacteria. According to the re-

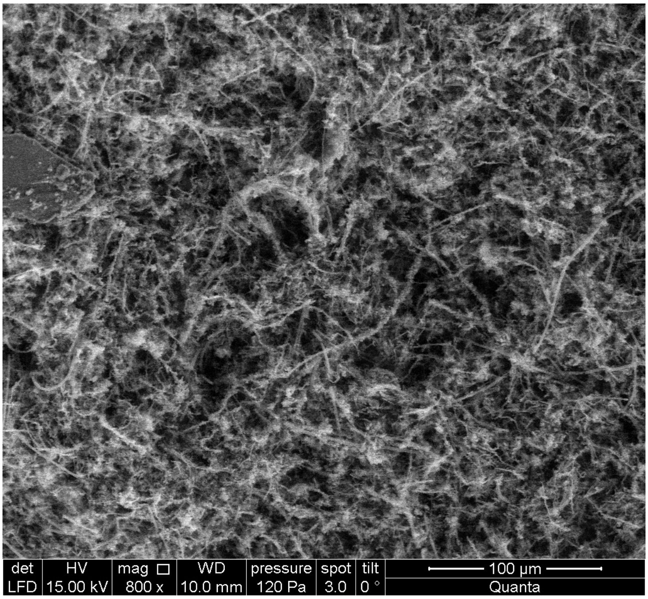

Fig. 10. Electronic image of the composition of the matrix structures in the washing waters of the biofilter 800×. Source: own study

sults of X-ray spectral analysis (Fig. 11), performed by the method of environmental scanning electron microscopy (ESEM) at low vacuum (5 Torr), it was established that the largest percentage in volume ratio is ferrum, 63.74%; oxygen 22.9% and carbon 4.03%. Nitrogen 0.9% and phosphorus 0.32% are present in small amounts. The latter three elements are part of *Gallionella* cells.

High concentration of oxygen atoms was explained by the entry of this element into the constituent components of the cell wall among which there are negatively charged groups (PO_4^{3-}; COO^-; OH^-), as well as to nanocrystals γ – FeOOH and goethite α – FeOOH, which are formed as a result of external-cellular activity of polysaccharides with Fe(II) ions. Thus, in the works of Neubauer (2002), it was noted that ferrobacteria have the ability to produce extracellular organic matrices that bind Fe(II) and accumulate it around the original matrix structures, which explains the high degree of its presence by weight and atomic composition both in individual cases and in agglomerates of matrix structures.

Fig. 12 (curves 2, 4) show the results of the combined operation of the bioreactor and the filter in the first 24 hours after washing.

As it can be seen from the above data, the bioreactor needs only 7–8 hours to restore the biological activity of ferrobacteria, part of which was removed from the module together with the matrix structures during washing (Fig. 10). During this period, the load is redistributed between the bioreactor and the filters. The filtrate has an excess of ferrum (II) compounds only in the first three hours.

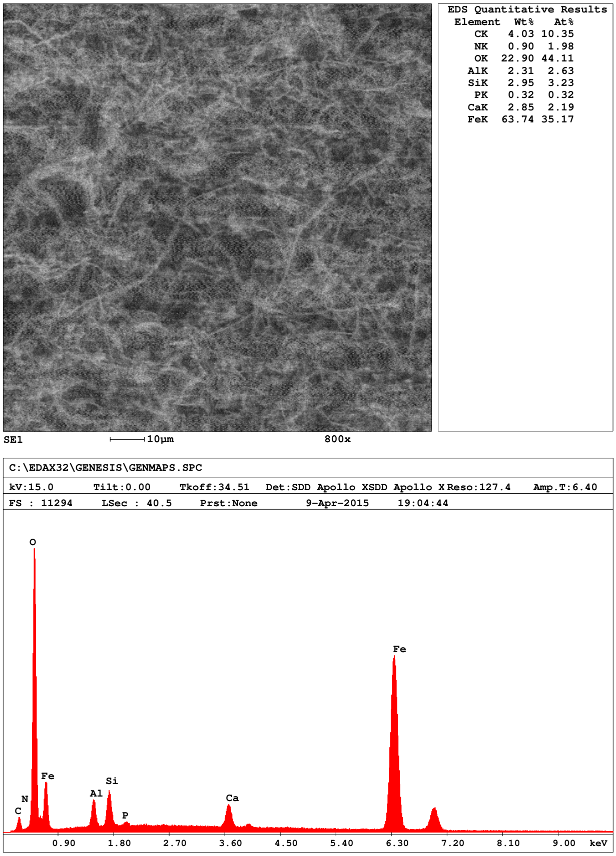

Fig. 11. X-ray spectral analysis of the composition of matrix structures in biofilter wash waters. Source: own study

Scheme III (Fig. 3 right). Combined aeration system – bioreactor with KTJT modules and constant magnet system 5–10 mT – polystyrene foam filters.

The results of comparative studies concerning operation of the installation (Fig. 3) according to the technology of biological deironing of underground waters on the biofilter with contact filling of kapron textured thread (Fig. 12, curve 2) and the operation of the bioabsorbent module under the influence of a constant magnetic field (Fig. 12, curve 4) indicate an increase in the efficiency of the iron removal process in the second option from 67% at the beginning of the filter cycle to 86% in the operating mode. This effect is explained by the increase in metabolic activity and biomass growth of ferrobacteria per unit of time (Fig. 4, curves 1–4 within the range of magnetic induction values of 5–10 mT).

Based on the results of the research, there has been developed the technology for treating weak acidic (pH 6.3–6.5), iron-containing (Fe^{2+} 6–8 mg/dm^3) underground

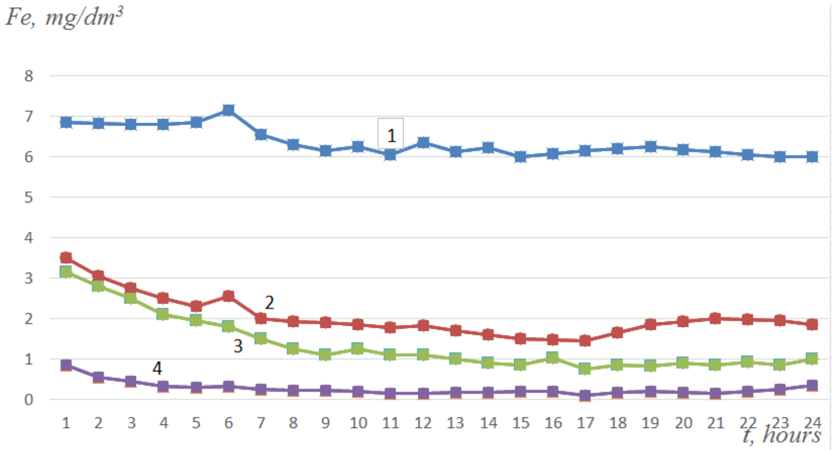

Fig. 12. Kinetics of oxidation of compounds of Fe(II) in the bioreactor: 1 – Fe(II) initial concentration; 2 – after the biofilter; 3 – after the biofilter under the influence of a constant magnetic field; 4 – after the filter with the technological scheme: biofilter-filter. Source: own results

waters with an increased content of carbon dioxide 80 mg/dm^3, hydrogen sulphide 4.0 mg/dm^3, dissolved organic substances 7–9 mgO$_2$/dm^3; low values of redox potential −700 – (−500) mV. The technology uses combinations of physical (aeration, influence of constant magnetic field) and biochemical (use of ferrobacteria consortia) methods, which together allow obtaining a synergistic purification effect.

4. Conclusions

There was developed biotechnology for treating weak acidic (pH 6.3–6.5), iron--containing (Fe^2+ 6–8 mg/dm3) underground waters with an increased content of carbon dioxide 80 mg/dm^3, dissolved organic substances 7–9 mgO$_2$/dm^3; low values of the redox potential −700 – (−500) mV, which is based on a combination of physical (aeration, influence of a constant magnetic field) and biochemical (use of ferrobacteria consortia) methods and allows obtaining a synergistic effect by increasing the efficiency of iron removal from 65–70% to 85–90%.

Induction values that boost (5–10 mT) or inhibit (130–150 mT) the development of bacteria were established.

The dynamics of the process of treating natural water from dissolved organic substances and Fe(II) cations by fixed biocenosis under the influence of a constant magnetic field with the force of 10–15 mT was studied.

Major technological parameters of the process were determined: filtration speed for the bioreactor 7–10 m/h, for filters 6–8 m/h; duration of filter cycles for the bioreactor is 2–3 weeks; for filters 44–48 hours.

Theoretical aspects of the influence of CMF on the processes of biochemical treatment of underground waters were substantiated.

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