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HYDROGEOLOGICAL ORIGIN OF WATER HARDNESS AND ITS REDUCTION BY ELECTROMAGNETIC TREATMENT OF PROCESS WATER AT THERMAL POWER PLANTS

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Abstract. *Relevance*. The high hardness of natural waters used in the heat-power sector of Kazakhstan has a hydrogeological origin: calcium and magnesium ions enter surface water and groundwater through the leaching of carbonate rocks and evaporites during natural water–rock interaction within catchment areas. When such water is heated in the boilers and heat exchangers of thermal power plants (TPPs) and combined heat and power plants (CHPs), dissolved hydrocarbonates decompose and precipitate as carbonate scale, which is a technogenic analogue of natural carbonate mineral formation. Scale sharply impairs heat transfer, increases fuel consumption and may cause equipment failures, while conventional chemical water treatment requires expensive reagents and pollutes water resources. *Objective*.

To substantiate an environmentally safe, reagent-free method for reducing carbonate scale formation based on the electromagnetic treatment of process water with a combination of high-power direct-current (DC) and alternating-current (AC) electromagnets, taking into account the hydrogeological origin of water hardness. Methods. A laboratory installation with a non-magnetic polypropylene pipeline was developed, in which tap water from the municipal network of Astana, supplied from the Vyacheslav (Astana) Reservoir on the Esil (Ishim) River and retaining the natural hardness governed by the hydrogeochemistry of its catchment, underwent a single-pass combined DC/AC electromagnetic treatment at a flow rate of 5 L/min. Forty water samples (20 taken before and 20 after treatment) were analysed in a blind laboratory experiment. *Results*. The treatment reduced pH from 7.73–7.89 to 6.0–6.1, the calcium content from 490 to 301 mg-eq/L and the magnesium content from 68 to 29 mg-eq/L; the combined DC/AC configuration was on average 10% more effective than previously tested permanent magnets. The crystallisation mechanisms of calcium carbonate during scale formation were shown to be analogous to the formation of natural travertines and speleothems. *Conclusions*. The results link the mineralogical mechanisms of carbonate crystallisation with the hydrogeochemical characteristics of the water source and show that reagent-free electromagnetic treatment can serve as an ecologically clean water-preparation technology for TPPs, CHPs and cooling systems using hard waters of the different hydrogeological provinces of Kazakhstan, as well as in the metallurgical and manufacturing industries.

Keywords: scale, water hardness, water treatment systems, electromagnetic treatment, hydrogeology, hydrogeochemistry, water–rock interaction, mineralogy

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СУ ҚАТТЫЛЫҒЫНЫҢ ГИДРОГЕОЛОГИЯЛЫҚ ТАБИҒАТЫ ЖӘНЕ ЖЫЛУ ЭЛЕКТР СТАНЦИЯЛАРЫНДА ТЕХНОЛОГИЯЛЫҚ СУДЫ ЭЛЕКТРОМАГНИТТІК ӨҢДЕУ АРҚЫЛЫ ОНЫ ТӨМЕНДЕТУ

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Аннотация. *Өзектілігі*. Қазақстанның жылу энергетикасында пайдаланылатын табиғи сулардың жоғары қаттылығы гидрогеологиялық сипатқа ие: кальций мен магний иондары су жинау алаптары шегінде «су–тау жынысы» жүйесіндегі табиғи әрекеттесу барысында карбонатты жыныстар мен эвапориттердің шайылуы нәтижесінде жерүсті және жерасты суларына түседі. Мұндай су жылу электр станциялары (ЖЭС) мен жылу электр орталықтарының (ЖЭО) қазандықтары мен жылу алмастырғыштарында қыздырылғанда, еріген гидрокарбонаттар ыдырап, табиғи карбонатты минералтүзілудің техногендік аналогы болып табылатын карбонатты қақ түрінде тұнбаға түседі. Қақ жылу беруді күрт нашарлатады, отын шығынын арттырады және жабдық апаттарына әкелуі мүмкін, ал дәстүрлі химиялық су дайындау қымбат реагенттерді қажет етіп, су ресурстарын ластайды. *Мақсаты*. Су қаттылығының гидрогеологиялық табиғатын ескере отырып, технологиялық суды тұрақты және айнымалы токтың қуатты электромагниттерінің комбинациясымен электромагниттік өңдеуге негізделген, экологиялық қауіпсіз әрі реагентсіз қақ түзілуін төмендету әдісін негіздеу. *Әдістері*. Магнитті емес полипропилен құбыры бар зертханалық қондырғы әзірленді; онда Есіл (Ишим) өзеніндегі Вячеслав (Астана) су қоймасынан берілетін және су жинау алабының гидрогеохимиясына байланысты табиғи қаттылығын сақтайтын Астана қаласының құбыр суы 5 л/мин шығында бір реттік аралас электромагниттік өңдеуден өтті. Қырық су сынамасы (өңдеуге дейін 20 және одан кейін 20) соқыр зертханалық эксперимент әдісімен талданды. *Нәтижелері*. Өңдеу нәтижесінде pH 7,73–7,89-дан 6,0–6,1-ге, кальций мөлшері 490-нан 301 мг-экв/л-ге, магний мөлшері 68-ден 29 мг-экв/л-ге дейін төмендеді; «тұрақты + айнымалы ток» аралас схемасы бұрын сыналған тұрақты магниттерге қарағанда орта есеппен 10%-ға тиімдірек болды. Қақ түзілу кезіндегі кальций карбонатының кристалдану механизмдері табиғи травертиндер мен спелеотемдердің қалыптасу процестеріне ұқсас екені көрсетілді. *Қорытынды*. Алынған нәтижелер карбонаттар кристалдануының минералогиялық механизмдерін сумен жабдықтау көзінің гидрогеохимиялық сипаттамаларымен байланыстырады және химиялық реагенттерді қажет етпейтін электромагниттік өңдеудің Қазақстанның әртүрлі гидрогеологиялық провинцияларының қатты суларын пайдаланатын ЖЭС, ЖЭО және салқындату жүйелері, сондай-ақ металлургия мен өңдеу өнеркәсібі үшін экологиялық таза су дайындау технологиясы бола алатынын көрсетеді.

Түйін сөздер: қақ, су қаттылығы, су дайындау жүйелері, электромагниттік өңдеу, гидрогеология, гидрогеохимия, су–тау жынысы әрекеттесуі, минералогия

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ГИДРОГЕОЛОГИЧЕСКАЯ ПРИРОДА ЖЁСТКОСТИ ВОДЫ И ЕЁ СНИЖЕНИЕ ПУТЁМ ЭЛЕКТРОМАГНИТНОЙ ОБРАБОТКИ ТЕХНОЛОГИЧЕСКОЙ ВОДЫ НА ТЕПЛОВЫХ ЭЛЕКТРОСТАНЦИЯХ

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Аннотация. *Актуальность*. Высокая жёсткость природных вод, используемых в теплоэнергетике Казахстана, имеет гидрогеологическое происхождение. Ионы кальция и магния поступают в поверхностные и подземные воды вследствие выщелачивания карбонатных пород и эвапоритов в процессе естественного взаимодействия в системе «вода — порода» в пределах водосборных бассейнов. При нагревании такой воды в котлах и теплообменниках тепловых электростанций (ТЭС) и теплоэлектроцентралей (ТЭЦ) растворённые гидрокарбонаты разлагаются и выпадают в осадок в виде карбонатной накипи, представляющей собой техногенный аналог природного карбонатного минералообразования. Накипь существенно ухудшает теплопередачу, увеличивает расход топлива и может приводить к авариям оборудования. При этом традиционная химическая водоподготовка требует применения дорогостоящих реагентов и способствует загрязнению водных ресурсов. *Цель*. Обосновать экологически безопасный безреагентный метод снижения накипеобразования, основанный на электромагнитной обработке технологической воды с использованием комбинации мощных электромагнитов постоянного и переменного тока и учитывающий гидрогеологическую природу жёсткости воды. *Методы*. Разработана лабораторная установка с немагнитным полипропиленовым трубопроводом. Водопроводная вода города Астаны, поступающая из Вячеславского (Астанинского) водохранилища на реке Есиль (Ишим) и сохраняющая природную жёсткость, обусловленную гидрогеохимическими особенностями водосбора, подвергалась однократной комбинированной электромагнитной обработке при расходе 5 л/мин. Сорок проб воды, включая 20 проб до обработки и 20 проб после неё, были проанализированы в рамках слепого лабораторного эксперимента. *Результаты*. В результате обработки значение pH снизилось с 7,73–7,89 до 6,0–6,1, содержание кальция — с 490 до 301 мг-экв/л, а содержание магния — с 68 до 29 мг-экв/л. Комбинированная схема «постоянный ток + переменный ток» оказалась в среднем на 10 % эффективнее ранее испытанной схемы с использованием постоянных магнитов. Установлено, что механизмы кристаллизации карбоната кальция при накипеобразовании аналогичны процессам формирования природных травертинов и спелеотем. *Выводы*. Полученные результаты позволяют установить взаимосвязь между минералогическими

механизмами кристаллизации карбонатов и гидрогеохимическими характеристиками источника водоснабжения. Электромагнитная обработка, не требующая применения химических реагентов, может использоваться в качестве экологически безопасной технологии водоподготовки на ТЭС и ТЭЦ, в системах охлаждения, эксплуатирующих жёсткие воды различных гидрогеологических провинций Казахстана, а также на предприятиях металлургической и обрабатывающей промышленности.

Ключевые слова: накипь, жесткость воды, системы водоподготовки, электромагнитная обработка, гидрогеология; гидрогеохимия, взаимодействие вода–порода, минералогия

Introduction. A fundamental aspect of the technological process for generating thermal and electrical energy is the heating of water. When water containing dissolved chemical elements is heated, scale precipitates on the heating surfaces of boilers, heat exchangers, and other thermal power equipment. This scale is a rather hard layer of mineral deposits that impedes the normal heat transfer process and creates a risk of overheating certain components of the equipment, potentially leading to accidents. The amount of scale formed on heating surfaces is directly dependent on the degree of water hardness and mineralization. Water resources in Kazakhstan are characterized by high hardness. Annually, scale renders a significant amount of thermal power equipment, shut-off valves, and water heaters inoperable. This problem is characteristic of both household water heaters and industrial systems.

From a hydrogeological standpoint, the elevated hardness typical of process and drinking water sources in Kazakhstan reflects the geological composition of their catchment areas. Calcium and magnesium ions enter surface and groundwater primarily through natural water–rock interaction — the leaching (dissolution) of carbonate rocks, evaporites, and other soluble mineral phases exposed within the drainage basin. Recent hydrogeochemical surveys of Kazakhstan's groundwater confirm that total water hardness varies widely across the country and is governed by regional geological structure, lithology, and water–rock interaction processes rather than by anthropogenic factors alone (Adenova et al., 2025). Water used in TPP and CHP process cycles in Kazakhstan is drawn predominantly from surface reservoirs fed by regional rivers; the geochemical composition of such inflow is likewise controlled by the lithology of its catchment area. Understanding this geological origin of hardness is essential for justifying descaling technologies, since the ionic composition and buffering capacity of water vary with the hydrogeological setting of its source.

Several well-known methods exist to combat scale, the most widespread of which is the chemical water treatment method based on adding reagents to the water to reduce its hardness. At thermal power plants (TPPs) or combined heat and power plants (CHPs), a system for treating process water is essential, as water is an indispensable coolant due to its availability and optimal heat capacity properties.

For the efficient operation of thermal power equipment, the water must undergo several cycles of purification and treatment. Chemically purified water is required. Since water contains dissolved hardness salts, these salts precipitate on heating surfaces upon heating, forming a hard layer of hydrocarbonate scale. Naturally, this scale reduces the thermal conductivity of boiler tubes or heat exchanger walls, leading to increased energy consumption and reduced productivity. Scale can also block the flow path, resulting in equipment damage due to increased pressure and temperature. Therefore, the fight against scale is a highly relevant area of research and the search for alternative methods to reduce water hardness.

One such method involves using a magnetic field instead of chemical reagents, which pollute the water and make it unsafe for consumption. One of the factors influencing scale formation is the pH level, which directly affects the process of solid deposit formation. This article presents an alternative water treatment method for TPPs and CHPs based on the use of a magnetic field. High-power DC and AC electromagnets act on the water flow. The foundation of the proposed method is not new, having been known and used in practice since the mid-20th century. The novel idea is to use a combination of DC and AC fields to achieve maximum efficiency in treating feed water and reducing the intensity of scale formation on heating surfaces. This method will allow for the reduction or complete elimination of harmful chemical reagents, necessitating the search for more environmentally friendly and less costly methods to combat scale formation. The application area for this method is the water treatment systems of TPPs and CHPs. It is worth noting that the operational cost of such electromagnetic systems is quite low compared to the costs of purchasing chemical reagents.

Literature review. A fairly detailed review of existing known methods of water treatment and scale control is presented in source (Moya et al., 2021). This source contains a wealth of information on developed magnetic systems and presents research findings. It has been established that scale is caused by salts of calcium $Ca(HCO_3)_2$ and magnesium $Mg(HCO_3)_2$ dissolved in water. When heated, these compounds decompose into $CaCO_3$ and $Mg(OH)_2$ with the release of CO_2, as well as sulfates ($CaSO_4$, $MgSO_4$) and chlorides ($MgCl_2$). It should also be noted that dissolved ions of Ca^{2+}, Mg^{2+}, Fe^{2+}, and Fe^{3+} are the cause of scale formation. When calcium, magnesium, and other salts are in a supersaturated solution, they begin to precipitate as solid deposits on the heating surfaces of heat exchangers and boilers (Mosin, 2011). Laboratory studies have been conducted using magnetic water treatment devices. The authors achieved certain effects from magnetic water treatment and demonstrated that a magnetic field can reduce scale (Busch et al., 2013).

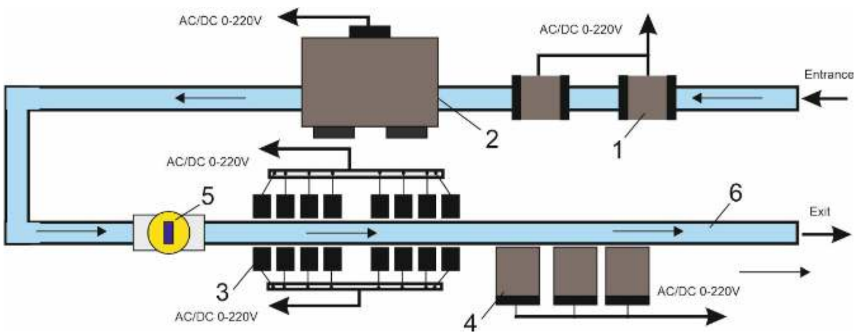
There is a publication that examines the electrochemical softening of tap water, presenting a new approach with zero chemical usage to reduce water resource pollution (Clauwaert et al., 2020). Magnetic water treatment is frequently encountered in literature related to water purification. For example, an article was found that discusses a method of magnetic water purification (Coey and Cass, 2000). Several publications are related to the study of the scale crystal formation process, including the nucleation and growth of calcium carbonate crystals in hard water (Karar et al., 2020) and the transformation of amorphous calcium carbonate into calcite and aragonite during shell formation (Kong et al., 2018). Hard water reduces not only the efficiency of thermal power equipment at TPPs and CHPs but also the cooling systems of metallurgical furnaces. An article proposes a device based on DC electromagnets to combat scale deposits in cooling systems (Mekhtiyev et al., 2021). As mentioned earlier, magnetic water treatment systems already exist, and article describes some of these devices (Mosin, 2011). There are continuous multi-stage precipitation reactors for water softening, but they are quite complex in design and are based on permanent magnets, which have temperature limitations and a service life of up to 7-8 years (Yu et al., 2019). A publication was found that provides a fairly detailed review of methods for reducing and preventing carbonate deposits. Various apparatuses and methods are presented (Naderi et al., 2024). This article enabled the creation of our own original design for a device for treating feed water for TPPs and CHPs based on a combination of DC and AC magnets. The authors have their own research related to the development of a proprietary design for a magnetic water treatment device, which was tested for a year on a household electric water heater. The device proved its effectiveness in protecting the electric heating element from scale (Mekhtiyev et al., 2024). There are also results from a conducted analysis of the magnetic field of an electromagnetic water purification device (Kozic et al., 2006). The problem of scale deposit formation on the heating surfaces of fire-tube boilers is considered in (Terebilov et al., 2017). This source formulates the problem and proposes the use of magnetic water treatment to solve it.

From the standpoint of hydrogeochemistry, carbonate scale formation in heat-power equipment is governed by the same equilibria that control the dissolution and precipitation of calcite in natural groundwater systems. The kinetics of calcite dissolution in CO_2–water systems (Plummer et al., 1978) and the principles of carbonate equilibrium in groundwater (Appelo, Postma, 2005) show that the calcium carbonate saturation state of water is determined by temperature, the partial pressure of CO_2 and the lithology of the aquifer or catchment. Heating of water in boilers shifts this equilibrium towards supersaturation and $CaCO_3$ precipitation — the same mechanism that produces natural carbonate cements, travertines and speleothems. Therefore, the efficiency of any anti-scale technology, including electromagnetic treatment, should be assessed with reference to the hydrogeochemical type of the source water, which in Kazakhstan varies considerably between hydrogeological provinces (Adenova et al., 2025).

Having studied the previously obtained research results, a laboratory setup was developed to conduct primary research on the combined effect of AC and DC magnetic fields on a flow of tap water (Ziyatbekova, 2026). These studies will be used further to create an experimental prototype of an electromagnetic water treatment installation.

Materials and methods. The developed experimental setup consists of a base on which a system of DC and AC electromagnets is mounted. An adjustable DC and AC power supply is used to create magnetic fields of varying power. The DC power supply has an adjustment range from 0 to 220 Volts, while the AC power supply has an adjustment range from 0 to 220 Volts, with a current frequency adjustable from 0 to 100 kHz. The AC generator can also produce various signal waveforms: sinusoidal, rectangular, and sawtooth. A Fluke 117 multimeter with a resolution of 0.1 V and an accuracy of 2.0% was used to measure current and voltage parameters. A Fluke 971 temperature and humidity meter with a temperature accuracy of ±0.5 °C was used for temperature control. A mechanical flow meter was installed in a section of the pipeline to measure the water flow rate. A coarse filter is installed at the inlet before the mechanical flow meter to collect various suspended solids present in the water and those formed after its electromagnetic treatment. The system also includes a mesh coarse filter. The core of the setup is a pipeline made of polypropylene pipes with an outer diameter of 25 mm and a wall thickness of 3.5 mm (PN 16, manufactured in Kazakhstan). The pipes were joined by soldering. The pipeline and fittings were soldered using a "CANDAN CM-03" soldering iron, 1500 W (manufactured in Turkey).

The experiments used only AC and DC electromagnets to create a combined effect. A portable TD 8620 teslameter (manufactured in China) was used to measure the magnetic field strength of the DC electromagnets. Water treatment was carried out at an ambient room temperature of 22°C. The water flow rate in the pipeline can be adjusted from 0 to 10 L/min. The experiment was conducted at a flow rate of 5 L/min. A key feature is that a non-magnetic plastic pipeline is used with the magnets located externally to the pipeline. Figure 1 shows a schematic diagram of the laboratory setup used in the research.



1 – coreless electromagnetic coils; 2 – AC motor stator; 3 – individual electromagnets with a core; 4 – electromagnets based on AC transformers; 5 – water meter; 6 – plastic pipeline.

Figure 1. Schematic diagram of the experimental setup.

Figure 2 shows a fragment of the setup where electromagnets of varying power and design are placed.

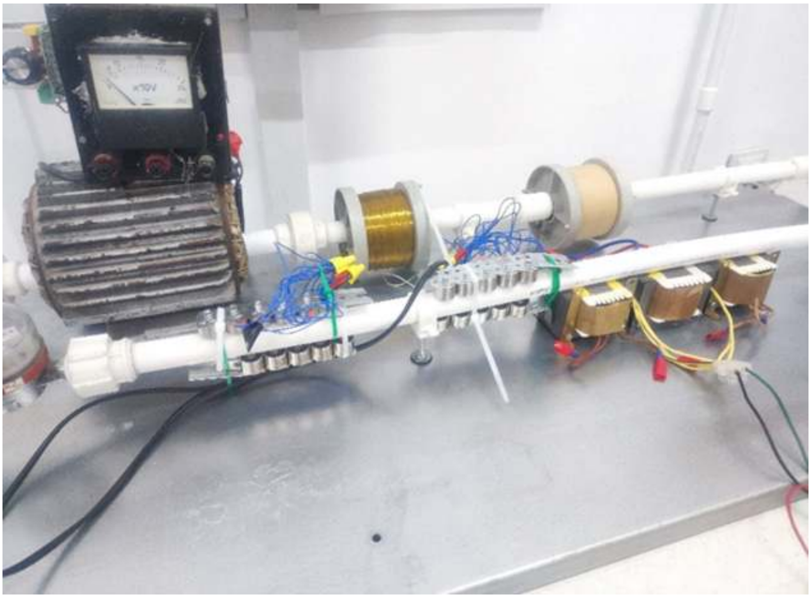


Figure 2. A fragment of the experimental setup for electromagnetic water treatment.

Water from the municipal water supply system of the city of Astana was passed through the pipeline. Water circulation was maintained by a pump with an adjustable flow rate. The water flowed through the pipeline system and was discharged into a receiving tank, from which water samples were collected. In this experiment, the water was driven through the entire length of the pipeline and subjected to the magnetic field only once. This procedure simulates a realistic water treatment scenario, as process water supplied to a boiler unit is typically treated only once in the production process.

The tap water used in the experiments was supplied from the municipal water-supply network of Astana, whose sole source is the Vyacheslav (Astana) Reservoir on the Esil (Ishim) River. Water from the reservoir undergoes conventional treatment (coagulation, filtration, disinfection) at the pumping-filtration station before entering the distribution network; however, its natural hardness — governed by the hydrogeological and geochemical characteristics of the Esil River basin — is not substantially altered by this treatment, making the tested water representative of process water used at TPPs and CHPs supplied from comparable surface sources.

Water samples were taken at the inlet of the system and at the outlet. A total of 20 water samples (100 ml each) were taken upstream of the treatment system, and another 20 samples were collected after the water passed through the magnetic system. In total, 40 plastic bottles with a capacity of 100 ml each were filled. Within half an hour, the bottles were transported to the laboratory for analysis to monitor changes in the chemical composition of the water. Each bottle was numbered without any indication of whether the water inside had been treated. This ensured that the laboratory personnel were unaware of the sample conditions (a blind test), which increased the accuracy of the experiment.

During the study, electromagnets were used to generate a magnetic field either along the axis of the water flow or perpendicular to it; in other words, the magnetic field lines were oriented longitudinally or transversely relative to the direction of water flow in the pipeline. Furthermore, two pole configurations of the electromagnets were tested: one with like poles facing the center of the flow, and another with opposite poles facing the center.

Results and discussion. Previous studies have been conducted using this experimental setup, but these experiments utilized only permanent magnets (Mekhtiyev et al., 2025). In the course of this research, a hypothesis was formed regarding the use of a combined effect on water by means of DC and AC magnetic fields. The studies conducted and the results obtained demonstrated an increase in the efficiency of water treatment and a reduction in hardness levels by an average of 10% compared to the results previously reported (Mekhtiyev et al., 2025).

The results of the analysis revealed the following: the pH values before treatment ranged from 7.73 to 7.89, while after treatment, the pH level was within the range of 6.0 to 6.1. The hardness levels before treatment were Ca^{2+} = 490 mg-eq/L and Mg^{2+} = 68 mg-eq/L. After treatment, these values changed to Ca^{2+} = 301 mg-eq/L and Mg^{2+} = 29 mg-eq/L.

The optimal magnetic field strength (H_{onm}) for disrupting the hydration shell can be determined from the equation:

$$H_{onm} = \frac{\tau_{02}\,\delta_{r}}{2\mu\,\mu_0\,\sigma_{r}\,a_{x}\,v_{x}}$$

Where

a_x – ionic radius;

τ_{02} – shear stress.

In the case of simultaneous exposure of water to crossed magnetic and electric fields (according to E.Kh. Rokhinson), the magnetohydrodynamic pressure in the electrode region is equal to

$$p_{м} = \mu\mu_0\frac{IH}{h}$$

Where

I – the current passing through the electrolyte;

h – electrode height.

Thus, when water ions move in a magnetic field, especially in its edge zones, conditions conducive to active ion association may be created — leading to fluctuations in their concentration and the disruption of ionic hydration shells. Under certain conditions, the edge zones of the magnetic field can act as a sort of 'factory' producing ion associates. However, this hypothesis requires experimental verification.

It, in turn, remains entirely unclear why the resulting ion associates, upon exiting the zone of increased concentration, do not instantly dissociate back into individual ions. If one disregards possible structural changes (a perspective we consider incorrect), then the primary role in stabilizing the associates must be attributed to the formation of nuclei of a new phase, which form quickly and decompose slowly. Pre-nucleation clusters of ions and molecules, which are necessary for accumulating a sufficient mass of material for the spontaneous emergence of stable nuclei of a new solid phase, may also play a role in this process. Pressure pulsations can also lead to the formation of gas bubble nuclei.

One can infer the presence of clathrate structures in the water, which play a key role in the formation of various hydrates. Such structures can exist for a longer time in water and can incorporate more ions or molecules that correspond to the size of their cavities. Considering several possible 'occupants' for these cavities, one can focus on the calcium ion. When calcium ions interact with water molecules, the most favorable process is the formation of the hexa-aqua complex $[Ca(H_2O)_6]^{2+}$, with an energy release of 630 kJ/mol.

The diameter of the calcium hexa-aqua complex (Figure 3), 0.516 nm, corresponds well to the diameter of one of the cavities in the clathrate structure (0.52 nm). This leads to the formation of large, metastable ions (Figure 3b) that can significantly alter the structure and properties of water. It should be noted that other impurities (e.g., chlorine molecules) may also be present in the clathrate cavities in addition to calcium ions.

The formation of such aqueous complexes requires overcoming a certain activation barrier, a process that can be facilitated by the short-term application of an electromagnetic field.

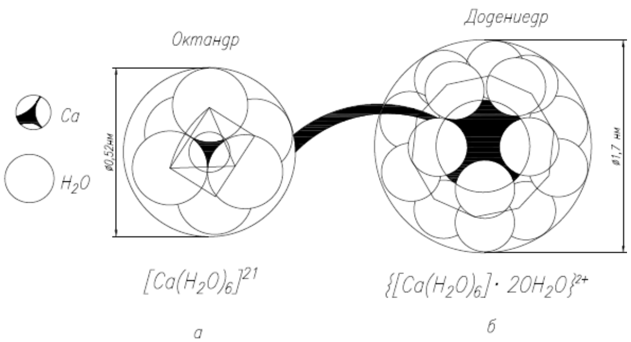


Figure 3. Stabilization of the calcium hexa-aqua complex $[Ca(H_2O)_6]^{2+}$ within the cavity of a dodecahedral water structure: a) the calcium hexa-aqua complex; b) the dodecahedral structure of water molecules.

It is worth noting that the crystallization mechanisms described above are not unique to technological scale formation: the same nucleation and growth pathways of $CaCO_3$ polymorphs (calcite and aragonite) govern the genesis of natural carbonate mineral deposits such as travertines and cave speleothems (stalactites and stalagmites), where supersaturated calcium-bearing solutions precipitate carbonate minerals upon degassing or evaporation (Luo et al., 2022). In this sense, the electromagnetically induced destabilization of hydration shells studied here can be regarded as an accelerated, controlled analogue of the natural water–rock interaction and mineral-precipitation processes studied in hydro geochemistry, offering a shared conceptual basis for interpreting scale formation as a geological-mineralogical, and not purely technological, phenomenon.

It should be emphasized that although the hexa-aqua complexes are metastable, their lifetime can extend to many hours. The observed changes in the structural characteristics of water following magnetic treatment (namely, an increase in the number and size of cohesive associate blocks separated by a disordered medium) are currently qualitative in nature. However, this may be sufficient to draw significant conclusions.

This specific change in the degree of water ordering after magnetic treatment is confirmed by numerous experiments and allows for the qualitative explanation of almost all changes in technological and biological processes observed in practice. Figure 4 shows a micrograph of several drops of magnetically treated water placed on a glass slide. The image shows that the formation of clustered crystal structures is evident.

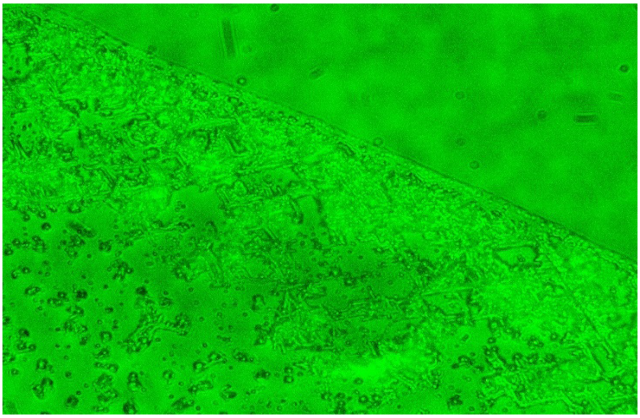


Figure 4. Micrograph.

Conclusions. Electromagnetic treatment has no adverse effects on human health. It is an environmentally safe method to obtain softened water quickly, without the need for maintenance or excessive costs. In this process, the saline properties of the water remain within the norm, and its fundamental composition is not critically altered. However, despite these advantages, magnetic action alone proved insufficient, which led to the development of the first variants of electromagnetic water treatment.

Based on a review of the scientific literature and the results of our own experiments, the following effects of using electromagnetic treatment on water can be identified:

- It accelerates and transforms the crystallization process, causing it to occur within the liquid flow rather than on surfaces.
- It intensifies sludge formation.
- It alters water quality parameters (increases pH; reduces the content of dissolved iron and manganese; decreases water hardness).
- It enhances adsorption processes.
- It affects the electrokinetic potential and aggregative stability of suspended particles, thereby accelerating their sedimentation and promoting the removal of various suspended matter from the liquid.
- Increase in the efficiency of heat supply systems (the removal of just 1 mm of scale can increase the overall system efficiency by up to 10%).
- Reduction in the intensity of scale formation, as well as the removal of existing old scale in boilers, water heaters, and heat supply pipes.
- Savings in fuel resources, which can amount to up to 40%, depending on the thickness of the scale.
- Increase in the service life of boiler feedwater lines, heating networks, and shut-off valves.
- Reduction of corrosion on the internal surfaces of heating network pipes, heat exchangers, and boiler feedwater lines.
- Stabilization of the chemical water treatment (CWT) system's operation, which reduces the impact of the "human factor" during filter regeneration.
- Reduction in chemical reagent consumption by up to 30%.

From a geological standpoint, the results obtained demonstrate that the efficiency of electromagnetic water treatment is directly related to the hydrogeochemical characteristics of the water source. Since water hardness in Kazakhstan is controlled by regional geology — the lithology of catchment areas and water–rock interaction in aquifers — the proposed technology should be adapted to the hydrogeological setting of the water intake of each specific TPP or CHP. Joint analysis of hydrogeological data and water-treatment parameters therefore becomes a necessary element in the design of scale-prevention systems, and the results of this study give the applied problem of scale control a geological and hydrogeological dimension consistent with the mineralogical mechanisms of natural carbonate mineral formation.

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