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DESIGN OF A MAGNETIC ACTIVATOR TO PREVENT SCALE FORMATION ON THE SURFACE OF TUBULAR ELECTRIC WATER HEATERS

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The object of this study is the processes of scale formation in electric water heating systems when using water of increased hardness.

The paper reports the design and testing of a magnetic activator to prevent scale formation on tubular electric heaters under hard water conditions without the use of chemical reagents. The device with neodymium magnets is installed on the supply pipeline of the water heater and solves the problem of scale formation without the use of chemical reagents.

The experiment was conducted for 90 days on a laboratory bench simulating the operation of a domestic water heater. Magnetic treatment of water reduces the overall hardness by 15–20%, the content of Ca^{2+} and Mg^{2+} ions by 35–50% and forms predominantly an aragonite modification of calcium carbonate, which is less prone to strong adhesion to the heating surface. The thickness of the scale layer on the heating element is about 0.5 mm versus 2 mm in the control sample, which reduced additional energy costs from 13% to 3%.

The effect is attributed to the action of magnetic field on the hydrate shells of hardness ions, which contributes to the formation of a less durable aragonite modification of calcium carbonate and disruption of the conditions for the crystallization of durable calcite on the heating surface.

A unique feature of the device is a combination of internal and external magnetic activators based on neodymium magnets that generate a stable magnetic field with high induction, as well as the presence of a sump and design solutions that prevent contact of the magnets with water. This enables a long-term and targeted effect of the field on the water flow, which improves the efficiency of treatment. The magnetic activator is effective in domestic and industrial water heating systems with hard water; it increases the service life of the equipment, reduces energy consumption, and decreases the need for chemical reagents

Keywords: magnetic field, hardness salts, energy efficiency, water treatment, electric heater, magnets, calcium, magnesium

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1. Introduction

The issue of scale formation on heating surfaces in water treatment and heat supply systems remains one of the key problems limiting the efficiency of both domestic and industrial heating equipment. In the context of constantly increasing requirements for energy efficiency and environmental friendliness of engineering systems, the scientific topic related to the prevention of hard salt deposits (primarily calcium and magnesium carbonate) remains highly relevant.

Scale disrupts heat transfer, increases specific energy costs, accelerates equipment wear and significantly reduces its service life. This is especially critical for water heating units, heat exchangers, boilers, and pipelines operated in regions with hard water, which is typical for the vast majority of territories in Kazakhstan, Central Asian countries, as well as many industrial zones around the world.

The widespread use of chemical water softening methods (reagent technologies), such as dosing acids, phosphates, or the use of ion exchange resins, is associated with a number of significant disadvantages. For example, high operating costs, the need for regular maintenance, difficulty in disposal, and most importantly, potential damage to the environment. In addition, chemical treatment changes the composition of water and in some cases may be unacceptable (for example, in the food industry, agriculture, or in autonomous water supply).

Against this background, physical (reagent-free) methods of water treatment, including magnetic, electromagnetic, and ultrasonic water treatment, are of particular importance. Among them, magnetic treatment remains one of the most discussed and promising technologies. The scientific topic related to the study of the influence of magnetic fields on the crystallization of hardness salts remains open, despite more than a century of history. Its goal is to find new methods for reducing scale formation for regions with water with increased hardness. This is due to the fact that water hardness negatively affects water heaters, boiler units, and heat exchange equipment. Such water requires increased consumption of chemical reagents and detergents. This problem causes significant economic damage and is typical for both production and domestic conditions.

Modern challenges – energy saving, environmental safety, the development of autonomous and compact engineering systems – require a return to this topic from new scientific positions: with the use of modern materials (for example, neodymium magnets), digital measurements, and verified models.

Thus, the relevance of the research area is predetermined by the need to devise effective, environmentally safe, and economically feasible technologies for preventing scale formation, alternative to conventional chemical methods. This determines the expediency of analyzing the current state of the problem and conducting new experimental studies in this area, which will be considered in the following chapters of our paper.

2. Literature review and problem statement

In [1], it is shown that magnetic fields can influence the behavior of hardness salts in water, as well as the scale formation process. The authors emphasize that the effect is especially noticeable with running water. However, issues related to the stability and reproducibility of the obtained effect under conditions of variable flow parameters and water composition have not been resolved. This method, related to physical methods of water treatment, is considered as an environmentally friendly alternative to chemical reagents. In [2], it is emphasized that the effect of a magnetic field is capable of changing the physicochemical characteristics of water – in particular, disrupting the structure of the hydrogen network of ionic hydration. Nevertheless, the mechanisms of changing the behavior of hardness ions remain unclear, especially in systems with long-term heating. Another point of view associates the effects of MOV with the action of the Lorentz force on charged particles in moving water. In [3], it was proven that in the presence of air bubbles, magnetic treatment of water is enhanced, which suggests the presence of complex resonance effects. However, the study was conducted under limited conditions and does not cover cases of stationary thermal load. The effect of the field on the surface properties of water has been proven; for example, some researchers observed a decrease in the surface tension of magnetically treated water and accelerated degassing of dissolved CO_2. The authors of [4] provide a critical review of the effect of a magnetic field on the crystallization of $CaCO^3$ indicating the possibility of a transition to the formation of aragonite, which is less prone to adhesion to surfaces. However, technical solutions ensuring the sustainability of this effect during long-term operation were not considered.

Experimental studies in the 2010s confirmed a number of effects of magnetic fields on salt solutions. A constant magnetic field can influence the crystallization of calcium carbonate by changing the ratio of polymorphic modifications. Usually, $CaCO^3$ precipitates in the form of calcite, a hard, difficult-to-remove sediment, but under the influence of a magnetic field, the proportion of aragonite increases, forming looser and more easily removed deposits. Aragonite has a different crystal lattice and a lower tendency to adhere strongly to surfaces, so its predominance has a beneficial effect on reducing scale. Thus, the effect of a magnetic or magnetic-pulse field (in the case of switching/pulsating electromagnetic devices) leads to changes in the water structure and ionic interactions, which are manifested in a change in the nature of crystallization of hardness salts. Work [5] demonstrates the effect of a magnetic field on the destruction of hydration shells of ions and facilitating their interaction with crystallization centers in the volume of water. Despite this, there is no correlation between laboratory results and operating conditions of domestic water heaters.

Scale deposits lead to a decrease in the throughput of water supply system pipelines and boiler units, and the efficiency of heat transfer processes in heat exchangers and water heaters is also reduced. This problem is typical for industrial enterprises, as well as for domestic water supply and heating systems. Study [6] considers the use of water treatment sludge for cleaning purposes but indirectly confirms that hardness salts remain a key pollutant and controlling them requires new approaches. Specific solutions for the effects of the magnetic field are not proposed in the work. Scale formation occurs when the concentration of a poorly soluble salt exceeds its solubility in water. This is usually due to changes in pH, temperature, gas evolution or pressure, which affect the solubility of salts, as well as the concentration or evaporation process. Work [2] emphasizes modern advances in the field of anti-scale magnetic treatment. However, it is noted that in most regions, including the Republic of Kazakhstan, chemical methods still prevail, which carry an environmental burden. Paper [7] reports a study on the scale structure in real water supply systems. The authors confirm that scale forms intensively with hard water, especially under temperature gradient conditions. However, methods for preventing deposits without the use of reagents are not considered. The problem of scale formation due to water hardness is typical for various industries, especially in the energy and thermal power industries [8]. Hard water contains a high concentration of dissolved minerals (calcium, magnesium), which cause the formation of solid deposits in heat exchangers, pipelines, and boilers at thermal power plants [9].

However, despite numerous publications, the following issues remain unresolved:

– reproducibility of the magnetic treatment effect;

– influence of the device configuration on the result;

– stability of the effect under long-term thermal load;

– lack of standardized test conditions;

– lack of experimental data under conditions close to real ones.

The reasons for this may be objective difficulties: high variability of the composition of natural water, lack of standards for the design of magnetic activators, difficulty in precise flow control in everyday life, as well as the lack of inexpensive universal solutions.

Our review of related literature showed that there are quite a large number of different methods for preventing or cleaning from $CaCO_3$ scale deposits, including magnetic or ultrasonic treatment, without the use of harmful reagents. Magnetic water purification systems use magnetic fields to change the physical properties of minerals in water, including chemical treatment and physical methods. For example, in the Republic of Kazakhstan, most chemical methods are used, including the use of acids and alkalis, which negatively affects the environment and water resources. Ion exchange filters are used less frequently but this is a rather expensive water softening technology. It is also possible to use physical methods of mechanical cleaning when deposits are removed using tools and devices [10]. There are studies in which the authors claim the low efficiency of magnetic water purification.

It should be recognized that part of scientific studies produced different results, some of which demonstrate an insignificant effect on water hardness and scale formation [11], but it is possible that the researchers made a mistake in conducting the experiments. Magnetic treatment methods are not yet perfect and require further research. Magnetic water treatment plants cannot yet become a full-fledged replacement for chemical water treatment systems at thermal power plants [12]. Papers [10–12] consider electromagnetic and mechanical methods of influencing impurities in water. The results are experimental in nature and do not provide data on the long-term stability of findings. There is contrary evidence that magnetic water treatment can significantly reduce the intensity of the scale formation process on heating surfaces. There is experimentally proven evidence of the effect of a magnetic field on the deposition of $CaCO_3$ scale in hard water [13]. It has been established that magnetic fields can induce electric currents in a conducting medium of solutions or suspensions with $CaCO_3$ [14]. But authors do not consider the influence of the composition of impurities and pH on the efficiency of magnetic treatment. The magnetic field is capable of influencing the process of alignment of magnetic particles in a solution or suspension with $CaCO_3$. Under the influence of the magnetic field, the process of formation of crystallization centers and growth of $CaCO_3$ crystals with a modified structure of the crystalline network occurs [15]. A direct quantitative characteristic of the change in the crystal structure is necessary, which is lacking in the cited study. The use of a magnetic field increases the dispersion and mixing of $CaCO_3$ particles in water, which reduces the amount of particles deposited on the heating surfaces [16]. Paper [17] reports the results of studies proving an increase in the influence of magnetic fields, which increased in the presence of air bubbles in water. It is noted that there is an interaction of the magnetic field and air bubbles; these factors are certain resonators and increase the efficiency of magnetic treatment of hard water. The release of mineral molecules is observed and the process of formation of crystallization centers in the volume of water is enhanced, but not on the heating surfaces. It can also be noted that electric and electromagnetic fields (for example, exposure to high-frequency current pulses) are also used for anti-scale purposes. Their action is similar to magnetic – it causes the movement of ions and polarization of particles in the solution, which disrupts normal crystallization on the surface. In work [18], the authors claim that magnetic water treatment is an important area of development of environmentally friendly water treatment technologies. The lack of uniform standards for the design and testing of magnetic systems is emphasized.

A wide range of devices for magnetic water treatment have been designed worldwide, from simple magnetic inserts in a pipeline to complex electronic systems that generate pulses of a given field shape. The simplest are magnetic softeners based on permanent magnets made of rare-earth alloys, such as Nd-Fe-B, with a configuration that ensures the intersection of the water flow with the field lines. They are installed on the outside of the pipeline (overhead systems) or in the form of an insert through which water flows. More advanced systems are electromagnetic devices, where a solenoid or coil creates an alternating or pulsating magnetic field in the flow zone. Pulse installations make it possible to vary the frequency, form, and gradients of the field, which, as noted above, can increase the efficiency of treatment due to the excitation of turbulence and inhomogeneities. As mentioned above, there are some issues with the recognition of the mechanism of magnetic treatment, the efficiency of the field and reliability. To understand these controversial issues, the authors of work [19] analyze the effect of the magnetic field on various stages of typical scale formation. The authors claim that the influence of the magnetic field on the process of crystallization center formation is present. The necessary factors for the formation of crystallization centers are a higher pH of the medium and the presence of a sufficient amount of magnetic impurities, which serve as templates for heterogeneous nucleation and crystal growth under the influence of a magnetic field. However, these sources do not offer universal solutions suitable for widespread implementation.

Given conditions in the Republic of Kazakhstan, hard water with an increased concentration of insoluble salts of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) is typical. As noted above, carbon scale deposits are formed when water containing calcium and magnesium ions is heated or evaporated. Therefore, water heaters, boilers, and heat exchangers suffer first. It has been proven that calcium and magnesium ions affect the growth of $CaCO_3$ crystals. During magnetic treatment of water, an unstable form of $CaCO_3$ is formed, which is called aragonite; if water treatment is not carried out, a more stable and durable form of calcite is formed [20]. Scale causes many problems during the operation of thermal power equipment at thermal power plants as it reduces its efficiency and creates conditions for breakdown or even an accident. To monitor scale, a sensor based on an optical fiber is proposed that can monitor the thickness of the hardness salt deposit layer on the walls of pipelines or heating surfaces of heat exchangers and water heaters [21]. The results of works [20, 21] discuss factors influencing the crystallization of calcium carbonate, including pH, temperature, the presence of other ions, and pressure. These factors are relevant for interpreting the results of magnetic treatment, but they were not taken into account experimentally in the cited paper, which reduces validity of the conclusions.

When exposed to chemical reagents, a magnetic field, or ultrasound, scale deposits can form unstable aragonite crystals. If hard water is directly fed to a boiler unit or water heater, then strong calcite deposits will form on the heating surfaces, which can only be removed mechanically [22]. The authors of work [23] presented a device for treating water with an alternating electromagnetic field. The authors claim that they have established a connection that magnesium ions affect the rate of scale formation on heating surfaces, and the combination of calcium and magnesium ions enhances the process of formation of solid deposits on heating surfaces.

Work [24] describes a technique for removing Mg^{2+} and Ca^{2+} ions from wastewater using chemical treatment, with the key parameter determining the efficiency of the process being the pH level. The studies demonstrate the results of field experiments in which the effect of an electromagnetic field on a flowing water stream was studied. As a result, the effect of an electromagnetic field led to a change in the process of scale formation by calcium and magnesium ions in water. The experiment showed that as a result of the effect of an electromagnetic field, calcium carbonate formed crystals of argonite, which has a lower density, rather than harder calcite. Argonite has brighter aggregation and softness than calcite [25]. However, these papers do not provide an analysis of the effect of neodymium magnets or their optimal location in the flow system.

For example, in paper [26], a designed electromagnetic DC device is considered, which has undergone practical testing in metallurgical production and was used in a water treatment system for cooling metallurgical furnaces. A magnetic activator was also designed to prevent scale formation in household electric water heaters. The problem of scale formation on heating surfaces is a very urgent issue for the Central region in the Republic of Kazakhstan because hard water is used in this region. The magnetic activator has a short payback period of up to 2 years due to the reduction of scale formation and energy costs and prevents the failure of the tubular electric heater. The magnetic field reduces the intensity of the scale formation process. All the obtained data have been experimentally confirmed [27]. However, these papers do not describe standardized test methodologies; insufficient detailing of the designs is provided.

Despite a large body of research in the area of magnetic water treatment, key issues related to the reproducibility of the effect, the stability of the results during long-term operation, and the lack of uniform standards for the design of devices have not yet been resolved. All this allows us to assert that it is advisable to conduct a study with the aim to design and experimentally verify a magnetic water treatment device with an optimized configuration.

3. The aim and objectives of the study

The aim of our study is to design a magnetic activator intended to prevent scale formation on the surface of tubular electric water heaters by physically affecting the flow of hard water with a magnetic field. This will make it possible to improve the energy efficiency of water heating systems and extend the service life of heating elements by reducing the intensity of scale formation. Subsequently, this will minimize the use of chemical reagents in water treatment under domestic and industrial conditions, especially in regions with hard water, such as the Central Region in the Republic of Kazakhstan.

To achieve this aim, the following objectives were accomplished:

– to design an experimental model of a magnetic activator using neodymium magnets, meant for installation on the supply pipeline of a water heater;

– to study the effect of a magnetic field on the processes of crystallization of hardness salts and scale formation on the heating surface under hard water conditions for 90 days on a laboratory bench simulating domestic use of a water heater;

– to determine the level of reduction in water hardness, concentration of Ca^{2+} and Mg^{2+} ions, scale thickness and energy consumption;

– to evaluate the economic and environmental efficiency of using a magnetic activator under actual operating conditions.

4. Materials and methods

The object of our study is the processes of scale formation in electric water heating systems when using water of increased hardness.

The hypothesis of the study assumed that when water is treated with a magnetic field, aragonite crystallization centers are formed in it, which, when heated, no longer settle on the heating surfaces of heat exchangers and boiler units. Water that has undergone magnetic field treatment of approximately 50 to 70%, depending on the degree of hardness, loses the ability to form scale deposits on the heating surfaces. It is assumed that the effect of a constant magnetic field on the flow of hard water changes the structure of ions and the crystallochemical properties of hardness salts, which leads to a decrease in the intensity of scale formation on the surfaces of heating elements.

During the study, the following simplifications were introduced: use of water from a single source, a constant heating mode, a limited time interval (90 days), analysis of a limited composition of the analyzed ions.

The study was conducted using an experimental approach and physical modeling of scale formation processes in water heating systems. The theoretical basis was provided by the provisions of hydrodynamics, magnetic field physics, and crystal chemistry, describing the effect of a constant magnetic field on the ionic structure of hard water.

For practical implementation, a laboratory bench was designed and constructed that simulated the operation of a household electric water heater. The structure included two identical cylindrical tanks with a capacity of 5 liters, each with a tubular electric heater with a power of 1500 W, equipped with a thermocouple and a temperature relay. Untreated tap water was supplied to one tank, and water that had previously passed through a magnetic activator was supplied to the second. This bench simulates a household electric water heater. Regular tap water was supplied to one water heater, and treated water that had passed through a magnetic activator was supplied to the other. Fig. 1 shows the general view of the laboratory bench connected to the city water supply system. Water passed through the heaters and was drained into the sewer; the same thing happens when using a household electric water heater.

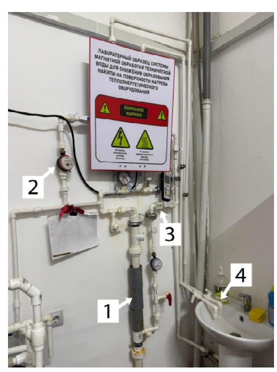


Fig. 1. General view of the laboratory bench:
1 — magnetic activator; 2 — mechanical flow meter;
3 — additional magnetic activator;
4 — pipeline for water discharge into the sewer

Fig. 2 shows two tanks with tubular electric heaters. Each tubular electric heater is equipped with a thermocouple to set and maintain the desired water heating temperature. The water heater has an inlet pipe for supplying water and an outlet pipe for removing already heated water. The bench is equipped with two flow meters for each tank, one pressure gauge for monitoring the pressure in the system, and an electronic eight-channel thermometer for monitoring water heating.

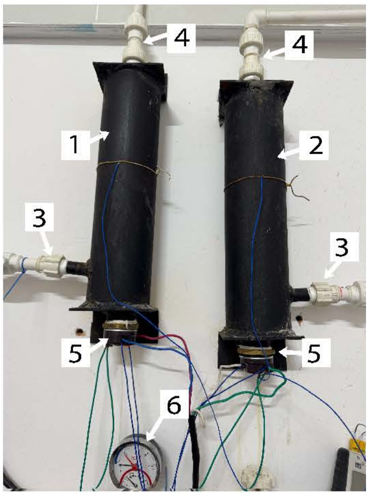


Fig. 2. Tanks with tubular electric heaters: 1 – tank for heating water not treated with a magnetic field; 2 – tank for heating water treated with a magnetic field; 3 – inlet pipeline; 4 – outlet pipeline; 5 – heating regulator with thermocouple; 6 – pressure gauge

The laboratory setup operates as follows: through inlet pipeline 1, water passed through ball valve 2 and pressure gauge 3 to the tee of divider 4, where it was divided into two flows A and B. The pipeline was divided into two independent pipelines, which were conditionally designated A and B. Mechanical flow meter 5 was installed on each pipeline. The setup is equipped with two identical tanks for heating water, each with tubular heaters of identical power. When water moves along direction A, water enters tank 8, is heated to a temperature of 80°C, and is discharged into the sewer through pipeline 10. When water moved along direction B, water first entered magnetic activator 6, then entered heating tank 9. Additional magnetic activators 7 were installed between activator 6 and tank 9. Heated water from tank 9 was discharged into sewerage through pipeline 11. Electric tubular water heaters were connected to electric energy metering and switching unit 12. The unit contained two electric meters and circuit breakers (Fig. 3).

The experiments were conducted in 2025 from the beginning of April to the end of June, over 90 days. During July, the obtained experimental data were processed. The experiment was conducted at the laboratory of the Karaganda Technical University named after A. Saginov, the city of Karaganda, which is the regional center. The city is located in the central region in the Republic of Kazakhstan with geographic coordinates: 73°07′ E and 49°48′ N. Karaganda region is the largest industrial zone; respectively, a significant number of industrial enterprises create conditions for intensive pollution of water resources with manganese, magnesium, sulfites, nitrites, iron. Water is delivered to the city of Karaganda through the Irtysh-Karaganda canal, 460 km long. Water is lifted by 22 pumping stations to a height of 420 meters. The water is medium and strong in hardness, the indicators lie within 5.4–12.7 mg-equiv./l. Express analyses were carried out using a Xiaomi TDS water hardness meter – a meter, which was also used to determine the amount of dissolved impurities in water and assess its water hardness. Two metal containers were used to heat the water, each equipped with a tubular electric heating element with a power of 1500 W with a temperature electromechanical relay and a thermocouple. Temperature measurements were made using two electronic digital devices NT9815 (measurement range –50 to +1050°C, error: ± 1°C) and TP–300 (measurement range –50 to +300°C, error: ± 1°C). Both devices are made in China.

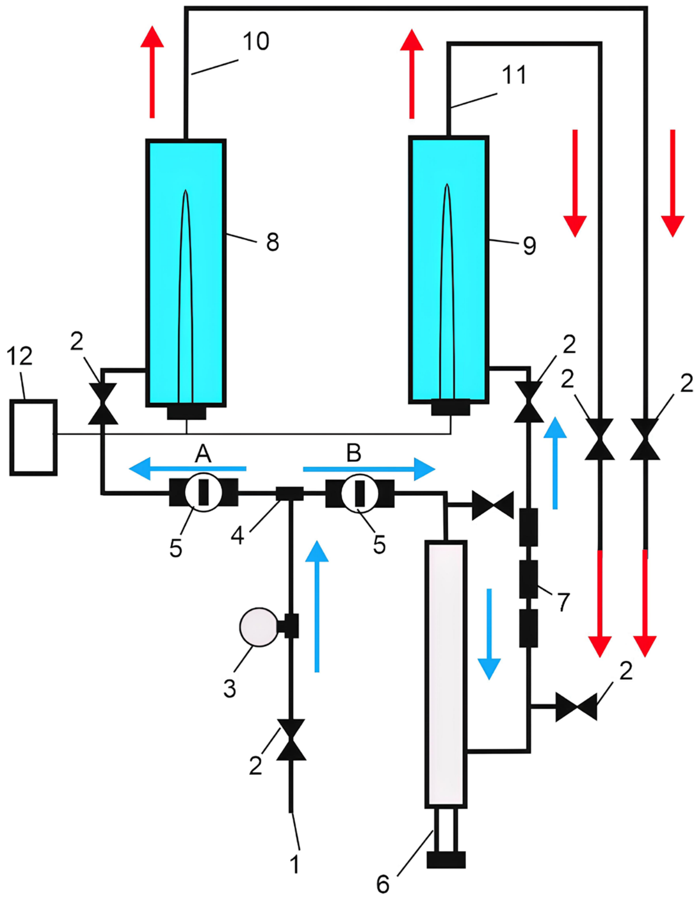


Fig. 3. Schematic diagram of the bench: 1 – inlet pipeline; 2 – ball valve; 3 – pressure gauge; 4 – tee separator; 5 – mechanical flow meter; 6 – magnetic activator; 7 – additional magnetic activator; 8, 9 – water heating tank; 10, 11 – pipeline for water discharge into the sewer; 12 – electric energy metering and switching unit

During the experiment, water samples were continuously collected. Water samples were taken at the inlet and outlet of the magnetic activator. The magnetic activator was equipped with two ball valves for collecting water samples at the inlet and outlet. Water samples were poured into plastic bottles, which were sent to the laboratory for analysis. The experiment was conducted for three months. A total of 30 water samples were collected from the system. Chemical analyses of the water were conducted randomly, approximately once every three days. Each time, 10 bottles of water were delivered to the laboratory, 5 bottles with treated water, and 5 bottles with untreated water. Each bottle had a volume of 100 ml and was numbered. Fig. 4 shows bottles with water samples.

Fig. 4. Water samples

Water samples were delivered to the laboratory for structural analysis using an Altami MET 5T microscope; visual observations of water drops from bottles containing treated and untreated water were conducted.

Water was supplied to the system from the municipal water supply of Karaganda, a region with characteristically high water hardness. The operation of the bench involved continuous heating and discharge of water, similar to household use. The experiment lasted 90 calendar days, with a constant load and a repeating cycle of heating and supplying water.

Water parameters (hardness, ion concentration, pH) were monitored using portable meters (including a Xiaomi TDS meter), as well as laboratory analysis of samples taken through special taps before and after magnetic treatment. Validation of structural changes in water was performed using an Altami MET 5T microscope with a magnification of up to 40 times.

To increase the reliability and adequacy of the solutions used:

– the experiment was conducted under conditions close to real household use;

– duplicate measurements of temperature and pressure were used;

– computer data processing was used in Microsoft Excel (USA) taking into account statistical parameters (significance level 95%, t-criterion);

– the heating conditions in both containers were identical, except for the presence of a magnetic field.

5. Results of examining a magnetic activator for protecting an electric water heater from scale formation

5. 1. Design of an experimental sample of a magnetic activator using neodymium magnets

The magnetic activator was made in the form of an internal insert with installed neodymium magnets N52 (40 pieces, 240 mT) and an external ring magnetic element. Its body provided a sump for suspended matter and excluded direct contact of the magnets with water. The design provided longitudinal and transverse action of the magnetic field on the water flow passing through the pipeline.

Fig. 5 shows a diagram of the magnetic activator. Water enters the body of magnetic activator 2 through inlet pipeline 1. The activator is made from a section of plastic pipe with a diameter of 65 mm. The activator body has two detachable couplings 3 in the upper part and lower part, which are necessary for installing the internal active part. The internal active part is made of a plastic pipe with an internal diameter of 21 mm and an external diameter of 23 mm, with a wall thickness of 2 mm. The wall thickness should be minimal since this affects the loss of magnetic force; the thicker the pipe wall, the higher the loss. Active part 7 contains 40 neodymium magnets N 52 with a diameter of 20 mm and a thickness of 5 mm with a force of 240 mT. Water passed between the internal walls in the cavity of activator 2 housing and internal activator 7 inside which there were magnets.

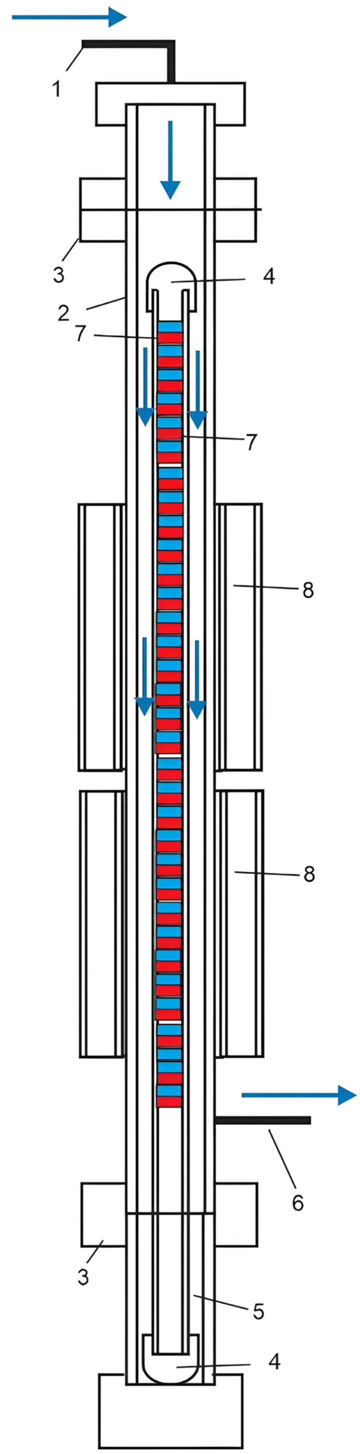
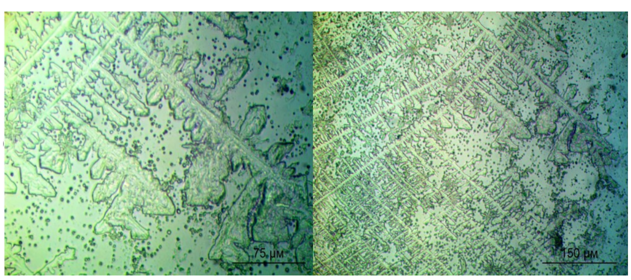


Fig. 5. Schematic diagram of the activator: 1 – input pipeline; 2 – activator body; 3 – detachable coupling; 4 – plug; 5 – sump; 6 – output pipeline; 7 – internal activator with magnets; 8 – external magnetic activator

External magnetic activator 8 is made of a ring magnet from the stator of a DC electric motor. Water was exposed to the magnetic field of the magnets located in the housing of internal activator 7 and external activator 8. Three additional magnetic activators were also used: neodymium magnets N 52 with a diameter of 20 mm and a thickness of 5 mm with a force of 240 mT; their design was discussed earlier in paper [27]. The section of the pipe in which the neodymium magnets are installed is closed on both sides with plastic plugs as the magnets should not touch the water since they will cause corrosion. In the lower part of the magnetic activator there is sump 5. Water is supplied from the top and passes along the entire length of activator 2 housing and reaches sump 5 where all suspended matter and contaminants remain. Outlet pipeline 6 removes the treated water from the activator and is located at a distance of 30 cm from the lower point of the activator. The active part of the activator consists of two parts: an internal tube with magnets 7 and an external part with ring magnets 8. In total, the activator has three external active parts.

5. 2. Studying the influence of magnetic field on the processes of crystallization of hardness salts and scale formation

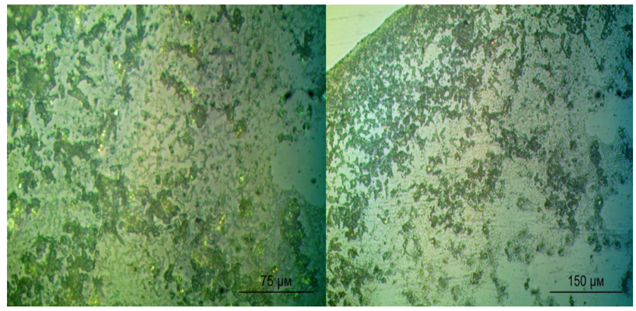
Fig. 6 shows a picture of a drop of water treated with a magnetic field, which was taken using an Altami MET 5T microscope. Visual observation showed that at 20 and 40x magnification, the treated water has a certain formed structure of aragonite or vaterite crystals, but the latter is quite rare. The treated water no longer causes scale deposits since crystallization centers have already formed, but as our studies have shown, not all bonds of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions are destroyed, some ions retain their structure. Accordingly, water treated with a magnetic field can cause scale deposits, but only on a much smaller scale. In addition, the formed sinicization centers are able to clean the heating surfaces from already formed deposits and destroy the structure of scale deposits.



a *b*

Fig. 6. Photograph of a water droplet treated with a magnetic field: *a* – 40x magnification; *b* – 20x magnification

Fig. 7 shows the image of a water droplet untreated by a magnetic field, taken with an Altami MET 5T microscope. Visual observation showed that at 40x magnification, untreated water does not have a specific magnetic field-formed structure of aragonite or vaterite crystals, but the latter is quite rare. Untreated water causes scale deposits since it contains quite a lot of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions while all ions retain their structure. The figure shows that there are no formed sinicization centers in the water droplet.



a *b*

Fig. 7. Photograph of a water droplet not treated with a magnetic field: *a* – 40x magnification; *b* – 20x magnification

Based on our experiments and observations, it was established that the magnetic field affects the flow of water passing through the pipeline as crystallization centers are formed. At the same time, hardness salts (Ca^{2+}) and magnesium (Mg^{2+}) were dissolved in the water, possibly other alkaline earth metals, which form hardness indicators. As can be seen in the figure, water not treated with a magnetic field has stable bonds of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions.

5. 3. Results of water hardness determination, concentration of Ca^{2+} and Mg^{2+} ions

The parameter value is $t = 2$, probability is 95%, and error is 5%. The processed experimental data showed that there are differences in water hardness values before and after magnetic treatment. An important indicator is the pH factor, which was 7.8 before treatment; after treatment, the pH was 6.9. The total water hardness changed from 9.5 mol/dm^3 before treatment to 7.2 mol/dm^3 after treatment. The hydrocarbonate values also changed from 122 mol/dm^3 before treatment to 91 mol/dm^3 after treatment. Before treatment, the Ca^{2+} ion values were 490 mg-equiv./l, and after treatment they were $Ca^{2+} = 311.6$ mg-equiv./l. There is a change in the Mg^{2+} ion values before treatment 69.8 mg-equiv./l, after treatment the Mg^{2+} values were 30.5 mg-equiv./l.

After the experiment was completed, the tubular electric heating elements were removed from each tank and inspected. After continuous operation for 90 days, each heating element had solid deposits of hardness salts. The heating element that worked with magnetic field-treated water had an average scale layer thickness of 0.5 mm, while the heating element that worked with untreated water had an average scale layer thickness of 2 mm. Based on the experimental data obtained, a diagram was constructed showing that with an increase in scale thickness to 2 mm, the energy overconsumption was 13%, and with a scale thickness of 0.5 mm, the energy overconsumption was only 3% (Fig. 8). With increasing scale, energy overconsumption will increase, and heat transfer will decrease. Since solid scale deposits conduct heat very poorly, more energy will be required to achieve the required heating temperature. With poor heat transfer, the metal tube of the electric heater will overheat and deteriorate, and the efficiency of the electric heater will decrease; its service life will be shortened.

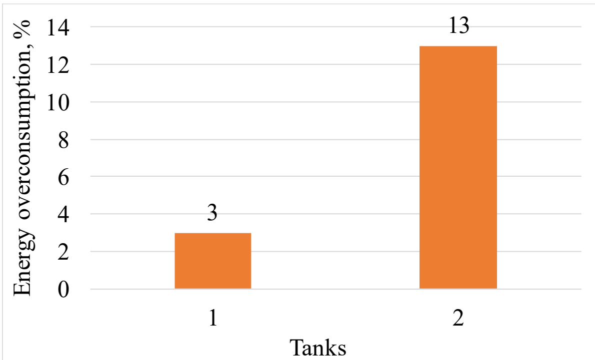


Fig. 8. Decrease in cooling efficiency depending on the thickness of the scale layer: 1 – tank with water treated with a magnetic field; 2 – tank with water not treated with a magnetic field

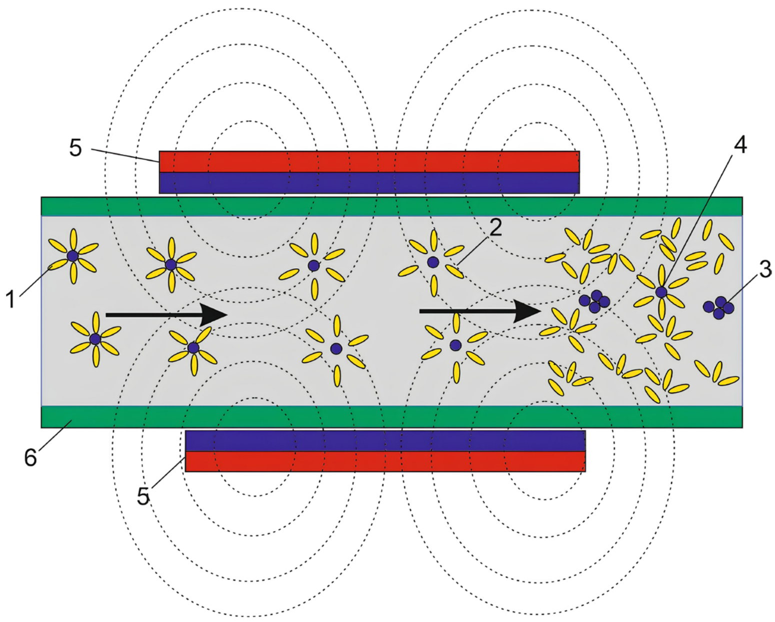


Fig. 9. Schematic diagram of the effect of a magnetic field on stable bonds of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions: 1 – magnetic field; 2 – bond destruction phase; 3 – crystallization center; 4 – hardness salt ions; 5 – permanent magnets; 6 – outer side of the pipeline

Fig. 9 shows a schematic diagram of the effect of a magnetic field on stable bonds of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. After passing through the magnetic field, the bonds of ions are destroyed and form crystallization centers of aragonite or vaterite crystals, which do not cause scale deposits when heating water and do not settle on the surface of the water. The formation process is affected by the water hardness and temperature: the higher the hardness and temperature, the higher the intensity of scale formation. The diagram shows the phases of transformation of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions into crystallization centers of aragonite or vaterite crystals. In the first stage, ions of hardness salts 1 pass through the magnetic field and go into the phase of bond destruction 2. After passing through the magnetic activator, crystallization centers 3 are formed, but some of the ions of hardness salts 4, namely calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, pass undamaged or with minor damage. It must be admitted that the remaining ions retain the ability to form scale, so after the experiment lasting 90 days, scale still formed on the electric heater. But the scale is much thinner than on the electric heater that worked with tap water not treated with a magnetic field. Permanent magnets 5 are installed on the outside of pipeline 6; this is necessary to protect the magnets from the effects of water. The thickness of the wall affects the force of impact on water; the thicker the wall, the less the force of impact. The north pole is directed toward the center of the water flow, and the south pole is directed away from the center of the water flow.

5. 4. Evaluation of the economic and environmental efficiency of using a magnetic activator under actual operating conditions

Economic efficiency implies reducing scale from 2 mm to 0.5 mm, which reduces heat loss and, as a result, reduces energy costs by 4.3 times (from 13% to 3%). At the same time, the service life of heating elements increases and the costs of their replacement and repair decrease. With the estimated cost of the activator and the cost of electricity in the region, the payback period of the device can be less than 2 years. The device does not require chemical reagents, which eliminates the contamination of wastewater with phosphates, acids, and other substances used in conventional water softening. The technology is a reagent-free and safe method of water treatment, which means it could be used in areas with limited environmental tolerances.

Economic efficiency involves the design and practical implementation of a device for reducing scale formation based on the use of a magnetic field, which could increase the efficiency of water heating and reduce electrical energy losses. That significantly extends the service life of domestic water heaters operating in hot water supply systems. The prospect of using this device in production, where this problem is quite acute, opens up. The effect may consist not only in saving fuel or energy for heating water but in reducing water pollution with reagents that reduce its hardness. The ecological effect includes a reagent-free water treatment system for boiler units.

Thus, the hypothesis has been partially confirmed; water that has undergone magnetic field treatment of approximately 50 to 70%, depending on the degree of hardness, loses the ability to form scale deposits on heating surfaces.

6. Discussion of results based on using the designed magnetic activator to reduce scale

The results of our experiments demonstrate a stable decrease in water hardness and a decrease in the intensity of scale formation when using the developed magnetic activator. The data obtained are consistent with a number of foreign studies confirming the ability of a magnetic field to change the morphology of calcium carbonate and promote the formation of a less dense aragonite structure instead of a harder and denser calcite structure [3, 13, 15]. This effect is especially important for the conditions of the Central region in the Republic of Kazakhstan where the initial water hardness exceeds 9 mol/dm^3, and conventional chemical methods of water treatment are associated with high costs and environmental risks [2, 9, 18].

Water treated with a magnetic field has a pronounced structure of aragonite crystals, which no longer cause scale deposits, because the crystallization phase has already passed (Fig. 6).

The obtained experimental results, including a 15–20% decrease in the total water hardness, a 35–50% decrease in the concentration of Ca^{2+} and Mg^{2+} ions, and a decrease in the scale layer thickness from 2 mm to 0.5 mm (Fig. 6), are explained by the combined effect of the magnetic field on the physicochemical properties of the hard water flow. This result is consistent with studies [5, 14, 16], which show that the magnetic field is capable of causing changes in the hydration shells of ions, facilitating their aggregation in the volume of water and subsequent removal in the form of microcrystals. Additionally, as noted in [17, 19], the presence of air bubbles in water can enhance the effect of magnetic treatment due to the interaction of the magnetic field with the gas phase, which probably also took place under the experimental conditions. Accordingly, water not treated with a magnetic field can cause scale deposits on a much larger scale than treated water.

The key factor is a change in the structure of the ionic environment of water passing through the active zone of the magnetic activator (Fig. 5 – diagram of the device). As shown in Fig. 6, 7, microscopic examination of the treated water samples confirmed the formation of aragonite and/or vaterite crystals in the samples after passing through the magnetic field. These forms of calcium carbonate are characterized by a loose structure and weak adhesion to the heating surface, in contrast to the compact calcite formed in the absence of treatment.

Of particular interest is the recorded ability of the treated water to gradually destroy existing scale deposits. Visual observations under a microscope showed the presence of aragonite and vaterite crystallization centers, which, according to [13, 20], can reduce the adhesion of solid deposits to the metal surface. This is consistent with practical results: the thickness of the scale layer on the treated heater was only 0.5 mm versus 2 mm on the control sample, which ensured a reduction in additional energy costs from 13% to 3% (Fig. 8). These data correspond to the mechanism described in our paper, based on the disruption of ion hydration shells under the influence of a magnetic field (Fig. 9). Ca^{2+} and Mg^{2+} ions, after passing through the activator, partially lose their hydration structure, which contributes to the formation of crystallization centers in the volume of water, and not on the heating surface. This is also confirmed visually and quantitatively, according to chemical analysis data from samples.

Water hardness is caused not only by the content of dissolved calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions but also by the presence of various minerals – limestone, gypsum, dolomite, etc. Even after partial removal of ions, they retain the ability to form scale on the heat exchange surfaces of boilers, heat exchangers and electric heaters. The transformation of calcium and magnesium ions into aragonite or vaterite crystallization centers is determined by the magnitude of magnetic induction and the length of the impact zone.

The designed magnetic activator has shown high practical significance and could be recommended for use in hot water supply and heating systems, especially in regions with hard water. Experimental data confirm its real environmental and economic feasibility, which makes this technological advancement relevant for both domestic and industrial use.

The limitations of our study are related to the following:

– the study does not provide the distribution of the magnetic flux density over the activator cross-section, which limits the possibility of accurate reproduction of the device;

– at this stage, the composition of impurities, except for Ca^{2+} and Mg^{2+}, which can affect the scalability of the effect, was not taken into account;

– real household and industrial conditions assume a variable flow, while the experiment was carried out under constant conditions.

A disadvantage of the study is the fact that the experiments were carried out on tap water in Karaganda, which has high hardness and a specific ionic composition. The results obtained may differ with different mineralization or the presence of organic impurities.

In the future, it is necessary to expand the research base using water from different regions and with different contents of dissolved salts. At the same time, the design of the activator must be improved; its efficiency and power must be increased in order to improve the process of reducing water hardness. The efficiency is compromised due to the fact that the thickness of the pipe walls is significant. The walls of the external and internal activator pipes must be further reduced in order to reduce the magnetic field losses in the material. As part of further advancement of the study, magnetic field modeling and measurements in different areas of the active zone could be carried out, as well as adding spectral analysis of the water composition and studying the effect of each component on the crystallization dynamics. Tests could also be carried out under conditions of variable flow and pressure to assess the stability of the magnetic treatment effect in dynamics.

7. Conclusions

1. An experimental model of a magnetic activator using neodymium magnets has been designed, intended for installation on the supply pipeline of a water heater. The experimental model of the magnetic activator is a structurally improved device designed for effective physical impact on the flow of hard water. The key feature of the activator is a two-level magnetic system, including an internal activator with 40 neodymium magnets of the N52 brand and an external ring magnetic element made on the basis of an electric motor stator. This configuration provides a combined longitudinal and transverse effect of the magnetic field on water, which increases the uniformity of treatment and increases the impact zone.

2. We have studied the effect of the magnetic field on the processes of crystallization of hardness salts and scale formation on the heating surface under hard water conditions for 90 days on a laboratory bench simulating domestic use of a water heater. It was found that magnetic treatment promotes the formation of predominantly aragonite, a loose modification of calcium carbonate that is less prone to sticking to the heating surface, unlike dense calcite formed without treatment. This ensured a decrease in scale thickness from 2 mm to 0.5 mm. A special feature of the experiment was long-term (90 days) continuous observation under the real parameters of urban water in Central Kazakhstan. The result is attributed to a change in the crystallization paths of hardness salts under the influence of a magnetic field and the formation of crystallization centers in the volume of the water flow.

3. Experimental data on the reduction of water hardness by 15–20% and the concentration of Ca^{2+} and Mg^{2+} ions by 35–50% when water passes through a magnetic field; scale thickness and energy consumption level were obtained and analyzed. Water treated with a magnetic field showed not only a reduced tendency to form new deposits but also a partial ability to destroy already formed scale, which distinguishes the effect from most known reagent-free methods. This result is confirmed by microscopic analysis and is attributed to the fact that the aragonite crystallization centers formed in the flow continue to act, interacting with existing deposits, facilitating their destruction. Unlike known devices, the proposed structure combines internal and external magnetic activators, generating a stable magnetic induction and an increased treatment zone. The effect is attributed to the effect of the magnetic field on the hydrate shells of hardness ions, disrupting their structure and promoting aggregation in the volume of water, and not on the heating surface.

4. The economic and environmental efficiency of using the designed device under actual operating conditions has been assessed. Reducing the scale thickness ensured a decrease in additional energy costs from 13% to 3%, which significantly improves the energy efficiency of the system. Compared with conventional chemical methods of water softening, magnetic treatment does not require consumables, does not pollute wastewater, does not cause corrosion of equipment, and has a low cost of operation. This makes the device especially promising for domestic and industrial water heating systems in regions with hard water as an environmentally friendly and energy-efficient alternative. The environmental effect is the reagent-free water treatment system for boiler plants. The economic effect involves not only saving fuel or energy for heating water but also reducing water pollution with reagents that decrease its hardness.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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