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DEVELOPMENT OF A MAGNETIC ACTIVATOR TO PROTECT AN ELECTRIC WATER HEATER AGAINST SCALE FORMATION

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The paper is dedicated to the research and development of a magnetic activator for the prevention of scale formation in electric water heaters, which is a pressing problem in regions with hard water, typical for Central Kazakhstan. During the operation of water heaters, salt deposits on heating elements lead to increased energy consumption and reduced efficiency. The developed activator uses powerful neodymium magnets that change the structure of the hardness salts in the water, preventing their deposition in the form of scale. Research has shown that the use of a magnetic activator can reduce water hardness by 15–20 %, resulting in a significant reduction in scale formation. In particular, under normal operating conditions, the thickness of the scale layer can reach 2–4 mm, but with the use of the magnetic activator this indicator is reduced to less than 1 mm. Descaling the heating elements not only extends the life of the water heater, but also reduces energy costs. Energy consumption is reduced by 10–15 %, as water heaters with less scale work more efficiently without requiring additional energy for heating. The paper also discusses the design features of the magnetic activator, the principles of its operation and the results of laboratory and field tests. Economic analysis has shown that the installation of the magnetic activator pays for itself within 1–2 years due to the reduction in limescale and energy costs. This makes it an attractive solution for private households as well as for industrial companies that use water heaters in their production process, as the proposed magnetic activator is an effective solution for protecting water heaters from the negative effects of hard water

Keywords: magnetic field, aragonite, water, scale, magnetic activator, neodymium magnets, efficiency

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1. Introduction

It is known that water hardness affects scale formation on various heating surfaces of heat exchangers, boiler units, boilers and other heat and power equipment. This problem is quite acute for regions with hard natural water. Solid deposits of hardness salts on heating surfaces and metal elements of water supply systems lead to their damage. In central Kazakhstan, water has a high enough hardness, which annually causes significant material damage in the home and at work. While in industry there are systems for descaling and reducing water hardness, the situation is much worse in households. Chemical reagents are used to control water hardness to combat this negative phenomenon, but the use of chemicals causes pollution of water resources. Every year thousands of people face the breakdown of washing machines, electric water heaters and other household appliances due to the formation of hardness salt deposits. Limescale leads to reduced efficiency of water heaters, reduces their operating life, and also leads to energy overconsumption. Scale is formed by the deposition of carbonate on the heating surface in the form of white scale and gradually increases, turning into a fairly strong layer that prevents heat exchange.

Therefore, research devoted to the development of a magnetic device for reducing water hardness is an urgent direction, as it can significantly reduce scale formation, extend the life of household appliances and reduce energy costs. In addition, the use of a magnetic field will reduce the amount of chemical reagents used and thus reduce their harmful effect on the environment.

2. Literature review and problem statement

The problem of water scale and hardness is the formation of insoluble salts such as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) when water rich in calcium and magnesium ions is heated or evaporated. The paper [1] presents the results of research into the effect of magnesium and sulfate ions on the nucleation and growth of $CaCO_3$ crystals. It is shown that when $MgSO_4$ is added, a significant delay in precipitation is observed compared to pure calcium carbonate solution. This is due to the fact that Mg^{2+} and SO_4^{2-} ions block the active sites of crystal growth, delaying their formation. Mg^{2+} also favors the formation of an unstable form of $CaCO_3$ – aragonite, while the more stable form of calcite prevails under normal conditions. In [2], they propose a method to predict Calcium Carbonate Precipitation Potential (CCPP) in aqueous systems using PHREEQC software. However, the study does not show results comparing the amount of scale precipitation in real systems with the calculated CCPP values. As part of the monitoring and identification of scale deposition, a portable fiber optic sensor is developed in [3]. To assess the scale formation, a method is used to evaluate the changes in light transmission through the optical fiber on its surface. The more scale is deposited on the optical fiber, the more its ability to transmit light is reduced, which is detected by the sensor. But there were unresolved issues related to preventing scale formation.

The paper [4] proposes an electrodeposition method to apply a stable PDA coating against $CaCO_3$ deposits and corrosion. Experiments showed that the developed PDA coating reduces the formation of calcium carbonate deposits by 55 % at 70 °C and 66 % at 90 °C compared to untreated metal surfaces. However, it is worth noting that the study focuses solely on the properties of the PDA coating, but does not provide a comparative analysis with other commercially available anti-corrosion and anti-scaling coatings. The paper [5] presents the results of applying an alternating electric field to prevent scale formation in the presence of magnesium ions. The study showed that the presence of magnesium ions significantly affects the rate of formation of carbonate deposits. As the magnesium concentration in the cooling water increases, the calcium carbonate precipitation process slows down. In [6], the performance of electrocoagulation (EC) process for water hardness removal using a synthetic solution with a salt concentration similar to brackish water is demonstrated. In this work, a laboratory electrochemical reactor with aluminum electrodes was used and the effects of different electrical potentials (3, 5, 7 and 9 V) and initial salt concentrations (3,300 and 7,400 mg/L) on the hardness removal efficiency and energy consumption were analyzed. But the maximum removal efficiency is only 25.83 % at 9 V and 7,400 mg/l concentration.

The study [7] presents modified valonium tannin extract (MVTE) as an antiscaling agent to prevent $CaCO_3$ formation in circulating cooling water systems. This paper reports the synthesis of MVTE based on valonium tannin extract, itaconic acid (IA) and 2-acrylamido-2-methylpropanesulfonic acid (AMPS) by free-radical polymerization. However, the efficiency of MVTE is highly dependent on the synthesis conditions such as temperature and reaction time. Any deviation from the optimum conditions can significantly reduce the antiscaling efficiency. The study [8] presented a method for removing Mg and Ca ions from wastewater based on chemical treatment and introduction of gaseous CO_2. It was found that the most significant factor affecting the removal efficiency of Ca ions is the initial pH of the wastewater. Maximum removal of Ca ions was observed at pH above 10. It should be taken into account that the application of this method requires regular cleaning and replacement of cathodes, which increases the operating cost of the system. In [9], a combined application of electromagnetic treatment (EMT) and chlorination is proposed to improve water quality in pools used for sea lion recreation. Experimental data showed a significant reduction in water turbidity of 41.5 % at high organic load and 49 % at low organic load. This indicates the ability of EMT to effectively remove suspended solids and prevent their further accumulation.

In [10], magnetic effects and EMT on water to reduce the likelihood of hard scale formation are discussed. Magnetic methods use permanent magnets to create a static magnetic field through which water passes. Exposure to a magnetic field causes a change in the behavior of calcium and magnesium ions in water, which affects the $CaCO_3$ crystallization process. As a result of this exposure, calcium carbonate precipitates as aragonite rather than calcite. Aragonite has a lower density and tendency to aggregate than calcite, making it less prone to form hard scale deposits. This approach was used in [11]. The study shows that EMT favors the formation of aragonite, a more stable and less prone to the formation of hard scale form of calcium carbonate. However, more research is needed to confirm the stability of the method under real operating conditions, especially at different temperature regimes.

The unresolved issue is the selection and placement of the design that will give the best scale reduction results. Also, approbation of the developed device in real domestic water supply systems. The initial scientific background and preliminary data were provided by the early works of the authors of the paper, which considered the use of magnetic and electromagnetic fields to reduce water hardness [12, 13].

3. The aim and objectives of the study

The aim of the study is to develop a magnetic activator for the protection of an electric water heater from scale formation and its practical testing.

To achieve this aim, the following objectives are accomplished:

– to develop a magnetic activator design;

– to study the process of scale formation on the surface of electric heaters in the period from 2022 to 2023 with the use of protective magnesium anode;

– to study the process of scale formation on the surface of the electric heater in the period from 2023 to 2024 using the proposed magnetic activator;

– to determine the dependence of energy overconsumption for water heating on the thickness of the scale layer on the surface of the electric heating element.

4. Materials and methods

The object of the study is a heating element on which scale is formed.

The hypothesis of the study is to use a magnetic field to prevent the formation of scale on the surfaces of electric heaters. It is assumed that the magnetic field created by permanent magnets allows creating crystallization centers for hardness salts, which further getting on the heating surface do not form scale deposits on it.

Simplifications have been made in the study because the water analysis was carried out once a year during the revision of the electric heater and the water hardness parameters were recorded before and after the activator. The final values of the water hardness parameters are averages over the entire study period from 2021 to 2024. The composition of the water was also not studied, considering the change of seasons.

The experiments were conducted in the period from 2021 to 2024. The place of the experiment is a private house located in the city of Karaganda. Karaganda is located in Central Kazakhstan, with a sharply continental temperate climate, geographical coordinates: 49°48′ N., 73°07′ E. It is the administrative center of the Karaganda region. The population of the city is 514,316. Water resources are polluted with manganese, magnesium, sulfites, nitrites, iron. The cause of pollution is industrial enterprises. The city of Karaganda is supplied with water at the expense of the Irtysh-Karaganda canal, as its own water resources are insufficient. The length of the canal is 458 km, depending on the terrain its width varies from 20 to 50 meters and depth from 5 to 7 meters. The canal originates from the tributaries of the Irtysh River and with the help of 22 pumping stations rises to a height of 418 meters at the final point, where the city of Karaganda is located. The canal is classified as a water source with a moderate level of pollution. The total hardness of water in different districts of the city ranges from 5.2 to 11.7 mg-eq/l on average. This water can be classified as medium and strong in terms of hardness, taking into account the norms (5–8 mg-eq/l and 9–12 mg-eq/l respectively). The water supply of Karaganda city is provided by a private company "Karagandy Su" LLP.

Independent measurements of water hardness indicators were made with the help of Xiaomi TDS-meter to determine the amount of dissolved impurities in water and assess its hardness. The scale of assessment of salt contamination is 0–9,990 molecules per 1 million molecules of water. The measurements showed that at the point of connection of the water heater to the water supply network, hardness values ranged from 582 to 614 mg/l at different times of the year and day. The water supplied to the private house went beyond the average indicator for the city and belonged to ultra-hard, the reason may be quite outdated piping systems.

Characteristics of the object of research tubular heating element with a capacity of 1,500 W from an electric water heater Thermex model ES50V are given in Table 1.

Table 1

Characteristics of the object of research

No.	Parameter name	Parameter value
1	Tank material	bioglass porcelain
2	Mains parameters, V	230
3	Max. electric power, W	1,500
4	Capacity in liters	50
5	Heating time at Δt 45° at max. power, min.	105
6	Max. water pressure, MPa	0.6
7	Min. water pressure, MPa	0.05
8	Max. water heating temperature, °C	75
9	Number of protective magnesium anodes	1

The experiment started in January 2021 with the installation of an electric water heater Thermex model ES50V at a private homeowner. The installation location was a bathroom (Fig. 1). The water heater was fixed on the bathroom wall and connected to the water supply system using polypropylene pipework. This water heater was used to heat water and provide hot water to the domestic water system. Electrically the heater was permanently connected to the mains electricity supply throughout and operated in automatic mode providing a constant water heating temperature of 70 °C. From January 2022 to January 2023 the heater was operated with no magnetic activator.

Fig. 1. Thermex model ES50V electric water heater in January 2022

Fig. 2 shows a photo of the cold pipework of a Thermex model ES50V electric water heater in January 2023 with magnetic activators installed.

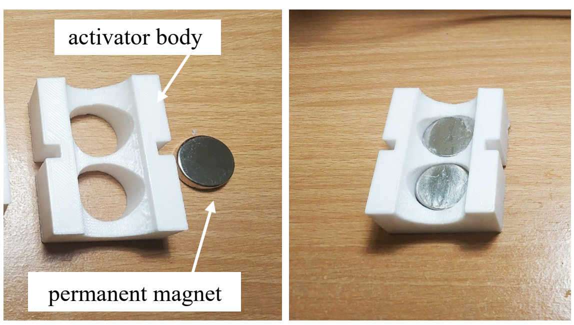
Fig. 2. Thermex model ES50V electric water heater in January 2022 with magnetic activators installed: 1 — magnetic activator; 2 — cold water pipework

The physicochemical methods of studying the dissolved hardness salts in the water before and after treatment were used to study the water composition and determine the pH factor. In addition, the Altami MET 5T microscope was used to visualize the formation of aragonite structures, which can be formed under the influence of a magnetic field on water. The hypothesis of a change in water hardness indicators under the influence of a magnetic field, leading to the formation of crystallization centers of hardness salts dissolved in water, was tested during the field experiment. To process the experimental data and plot the dependence graphs, the Excel program capabilities were used.

5. Results of research of a magnetic activator to protect an electric water heater against scale formation

5. 1. Development of a magnetic activator design

To realize the protection of the tubular heating element against scale formation, two in-house designed magnetic water activators were manufactured. From January 2023 to January 2024 the heater was operated with two magnetic activators. The housing of the magnetic activator is made by 3D printing from ABS plastic (Fig. 3). The housing is divided into two parts, each part contains 2 neodymium magnets N 52 with a diameter of 20 mm and thickness of 5 mm with a force of 240 mT. Total one activator contains 4 magnets, which are directed to meet each other by the north poles N. Taking into account the losses, the magnetic field induction force in the center of the pipeline averaged 68 mT.



a *b*

Fig. 3. Activator design: *a* – disassembled; *b* – assembled

Fig. 4 shows the scheme of magnets location and impact on the water flow, as well as the directions of pipelines supply to the electric water heater and the places of installation of magnetic activators.

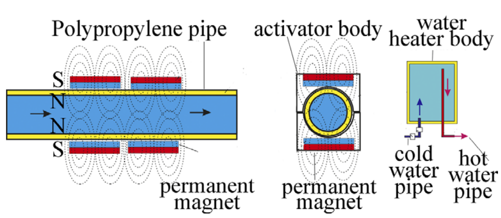
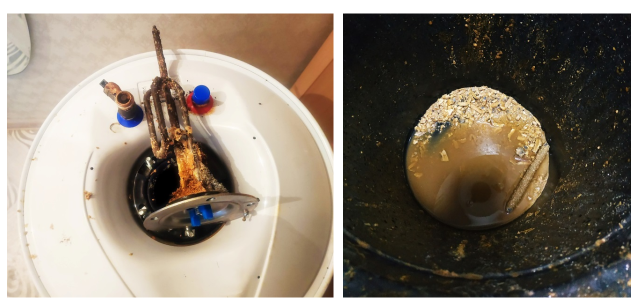


Fig. 4. Simplified diagram of the effect on water flow: *a* – water heater diagram; *b* – pipe with magnetic activator diagram; *c* – magnetic activator operating diagram

The magnets are placed outside the pipe to direct the magnetic field across the water flow, improving the effect on hardness ions. This design solution simplifies installation by eliminating the need to cut the pipe and couplings. The use of 3D printing has significantly reduced the cost of the magnetic activator compared to existing analogs made of metal.

5. 2. Study of the process of scale formation on the surface of electric heaters in the period from 2022 to 2023 with the use of protective magnesium anode

The experiment was conducted for three full years from January 2022 to January 2024. The first revision was performed in January 2023 after one year of continuous operation at a near limit temperature of 70 °C. When the electric heater was removed, it was found that over a year of operation at a water heating temperature of 70 °C, hard deposits of hardness salts had formed on the heating element and on the tank walls. Initially, to protect the water heater from scale and corrosion, a magnesium anode was factory installed on the water heater, which had become unusable and completely destroyed. Visual inspection of the 1500 W tubular heating element, which was used for heating rather hard water, showed that the magnesium anode did not provide full protection against scale formation and corrosion development on the tank walls, especially the upper part, where the most heated part of the water is located. Visual inspection also showed that the tank walls had hard deposits of hardness salts and corrosion centers. The 1500 W tubular heating element was inspected and found to be functional and still intact. It was then mechanically cleaned of scale deposits on its surface. It was almost completely free of solid deposits and after rinsing, the tubular heating element was reinstalled. Since January 2023 the water heater was again put into operation practically at the limit water heating temperature of 70 °C, but without magnesium anode. This is contrary to the manufacturer's recommendations, which prohibit the operation of the water heater, as the electric heater remains unprotected from scale and corrosion, as well as the tank itself. Fig. 5 shows a photo of the electric tube heater removed from the tank, as can be seen from the photo the level of contamination is quite serious. Scale creates a risk of overheating of the electric heater and its failure. The photo also shows that the protective anode was destroyed and when removed, it separated from the attachment point and could not continue to fulfill its functions. When the protective anode was in use, there were quite a lot of hardness salt deposits on the bottom of the heater tank, which separated from the surface of the anode when it was removed. The amount of deposits can be seen in the photo, and it can also be seen that the anode has collapsed at its base.



a *b*

Fig. 5. Photo of the electric tube heater removed from the tank during the first inspection: *a* – photo of the fork water heater from the side; *b* – formed sediment at the bottom of the tank

Deposits of hardness salts were not only on the surface of the electric tube heater, but also on the inner walls of the tank, especially in the lower part of the tank. Instrumental measurements showed that the scale layer on the surface of the electric heater could be up to 4 mm thick and in some places even thicker, and in the bottom part of the electric heater there was a significant deposit up to 30 mm thick. The upper part of the tank is corroded. Fig. 6 shows photos of the inside of the water heater tank, the solid deposits of hardness salts are characteristic of the bottom part of the tank and go up to the level of 1/3 of its height.

a *b*

Fig. 6. Photo of the inside of the water heater tank during the first revision: *a* – photo of the inner surface of the water heater tank; *b* – detail of scale on the water supply pipe

Closer to its top the deposits are less, they are already formed as separate growths. The tank has not been cleaned. After completion of the inspection and cleaning, the heater was reassembled and connected to the water supply system.

5. 3. Study of the process of scale formation on the surface of the electric heater in the period from 2023 to 2024 using the proposed magnetic activator

The second phase of the experiment lasted from January 2023 to January 2024. In January 2024, another revision was carried out. The difference from the previous term of the experiment is the absence of the magnesium anode, which had collapsed and was not adopted again. A magnetic water treatment method was used to protect the tubular heating element to prevent scaling. Fig. 7 shows a photo of the removed tubular electric heater.

After a year of continuous operation, almost at the limit temperature of 70 °C with two magnetic activators, the tubular heating element was covered with only a millimeter layer of deposits, but the deposits were not in a solid state and easily separated from the surface of the electric heater. A photo of the inside of the tank at the time of the inspection is shown in Fig. 8.

a *b*

Fig. 7. Photo of the removed tubular electric heater during the revision: *a* – side view; *b* – top view

Fig. 8. Photo of the inside of the tank at the time of the second revision

The amount of sediment on the bottom of the tank was negligible, within 30 cm, compared to about 400 cm collected during the first revision. The sediments on the inner walls of the tank did not grow and remained almost at the same level of the walls. It should be noted that the sediments have become softer and more easily broken down. Fig. 9 shows a photo of the sediment formed on the bottom of the heater tank.

Fig. 9. Photo of sediment formed on the bottom of the water heater tank January 2023 revision and January 2024 revision

It should be assumed that the magnesium anode is more necessary to protect the walls of the water heater tank from corrosion than from scale formation, which is significantly influenced by the hardness of tap water. It can be used as a means of passive protection of the inner surface of the tank and the heating element against electrochemical corrosion. A magnesium alloy rod was used, which is more active than the steel walls of the tank and reacts with the oxygen dissolved in the water. The anode is gradually oxidized and destroyed and its protective properties are reduced. Experimental results have shown that the magnesium anode is not able to provide full protection for the surface of a tubular electric water heater operating in hard water.

Electrical parameters were measured before and after each revision. The power consumption was monitored against the time of heating and reaching the water temperature of 70 °C.

It was recorded that the electric water heater used less energy and time to heat 50 liters of water when initially switched on than after two years of operation before the first revision in January 2023. During the period of operation from January 2022 to January 2023, a layer of scale formed on the surface of the tubular electric water heater. The thickness of the layer of solid deposits varied from 2 to 4 mm, with a particularly thick layer forming at the bending points of the tubular heater. Then after mechanical cleaning of the surface of the tubular electric water heater, the electrical parameters and heating time returned to the original value. After the period of operation from January 2023 to January 2024, the surface of the tubular electric water heater developed foci of scale with a layer thickness of less than 1 mm. Mostly the scale formed in places where the surface could not be completely cleaned.

5. 4. Determination of the dependence of energy overconsumption for water heating

On the basis of the processed experimental data, a graph of the dependence of electric energy overconsumption on the thickness of scale on the surface of the electric water heater was plotted. It can also be noted that there is a danger of failure of the tubular electric heater due to overheating and increase of the wall temperature in the places of scale formation. This leads to a reduction of metal strength and destruction of the tubular electric heater of the heater. The increase of the scale layer reduces the intensity of heat exchange between the heating surface and water, the power of the electric heater decreases depending on the thickness of the scale layer and the heating time increases accordingly. It is found that at the formed layer of scale on the surface of the tubular electric heater from 2 to 4 mm the power drop is about 18 to 27 %.

As can be seen in Fig. 10, the thickness of scale directly affects the energy consumption for heating one liter of water. The dependence is linear and expresses a direct dependence on the growth of energy consumption. Scale formation not only affects the energy costs, but can also cause breakdown of the electric heater, which is an economic loss for domestic hot water systems. Replacement of an electric heater always involves some material costs, so reducing the scale layer will prolong the life of the electric heater.

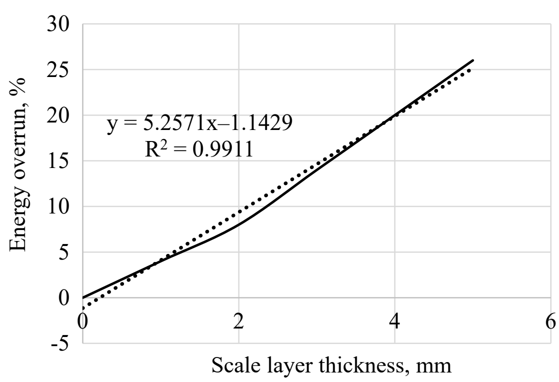
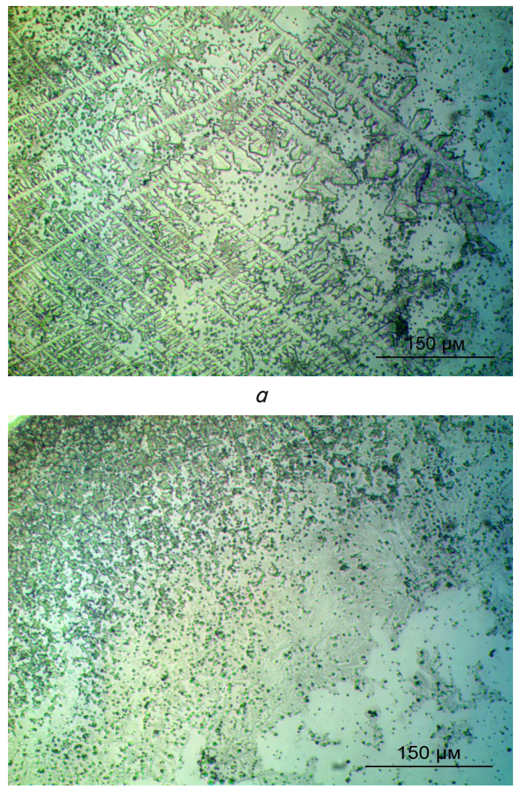


Fig. 10. Dependence of energy overconsumption for water heating on the thickness of the scale layer on the surface of the electric heating element

In the process of research, water was taken from the hot water supply system for laboratory analyses. Water was taken before and after the magnetic activator. The results of the analyses are as follows: the pH factor values changed from 7.73 to 8.1 after treatment and from 6.35 to 6.55 before treatment. Before treatment, it is clear that the environment is slightly acidic, the pH was determined by immersing universal indicator paper in the water being tested. It can also be noted that before treatment, the values were as follows: Ca^{2+}=510 mg-eq/l and Mg^{2+}=66.825, after treatment Ca^{2+}=314.685 mg-eq/l and Mg^{2+}=30.375 mg-eq/l.

In addition, the studies were carried out using the Altami MET 5T microscope for visual observation of water droplets before and after its treatment with a magnetic field. Fig. 11 presents photos obtained with the help of the microscope on which the process of aragonite crystallization centers is visible.



a

b

Fig. 11. Water microscope photos:
a – after treatment; *b* – before treatment

The obtained results coincide with the results of studies conducted earlier [13]. Aragonite crystals do not cause scaling as they have already passed the crystallization phases.

6. Discussion on the results of the application of the developed magnetic activator for scale reduction

The design of the proposed magnetic activator allows for easy installation and removal without complicated tools, simplifying maintenance and making it more affordable for home use. The activator uses powerful neodymium magnets with an induction at the center of the pipe of approximately 68 mTl, which provides sufficient magnetic field strength.

The results of the study showed that the use of the developed magnetic activator significantly reduces water hardness and decreases scale formation on the heating elements of an electric water heater. It is important to consider the key aspects and numerical indicators that illustrate the effectiveness of the proposed solution.

The conducted experiments showed that the installation of the magnetic activator on the water system resulted in an average 15–20 % reduction in water hardness. This significant reduction in hardness had a direct effect on the amount of scale formed on the surface of the heating elements. In particular, a reduction in scale thickness from 2–4 mm to less than 1 mm was recorded (Fig. 9), confirming the effectiveness of the magnetic action. The magnetic field induction value created by the activator was 68 mTl, which was sufficient to achieve the specified results.

During two years of operation of the water heater without the magnetic activator, a layer of scale with thickness from 2 to 4 mm was formed on its surface (Fig. 5), which resulted in a reduction of thermal efficiency of the heater by 18–27 %. In contrast, when the magnetic activator was used, the scale thickness did not exceed 1 mm (Fig. 7) and the reduction in thermal efficiency was minimal – about 5–7 %. This allows us to conclude that the magnetic activator is comparable in efficiency with chemical methods [8], however, it does not have their disadvantages, such as water contamination with chemical reagents. The use of the magnetic activator has a number of advantages and first of all it is its environmental friendliness.

Long-term operation of the magnetic activator showed that the amount and density of scale deposits on the internal walls of the water heater tank decreased. During the second inspection, two years after the activator was installed, the amount of sediment at the bottom of the tank was only 30 cm^3, a significant reduction from the 400 cm^3 found during the first inspection. In addition, the sludge was softer and easily separated from the heater surface, making it easier to remove and maintain the equipment.

An economic analysis showed that reducing the amount of scale on the heating elements resulted in a 10–15 % reduction in electricity consumption due to more efficient heat transfer (Fig. 10). In the long run, the installation of a magnetic activator pays for itself by reducing operating costs and extending the life of the equipment.

The limitation of the study is that the activator can only affect the water flow through the pipeline. If the water does not move, there is no effect of crystallization center formation. Small resolving power of the Altami MET 5T microscope is a disadvantage. In future studies, a more accurate microscope will be used to study the crystallization structure of aragonite. It should be noted that the effectiveness of a magnetic activator can depend on the specific water composition and operating conditions. For example, in cases of extremely hard water (hardness greater than 600 mg/l), further optimization of the activator design or combination with other water treatment methods may be required. Further research could be directed at studying the effect of magnetic fields of different intensities and frequencies on scale formation, as well as at developing activators adapted for use in industrial water supply systems.

7. Conclusions

1. As a result of the study, an experimental sample of a magnetic activator designed to reduce water hardness and scale formation on electric heater surfaces used in domestic hot water supply systems was developed and tested. The activator was manufactured using neodymium magnets providing sufficient magnetic field strength to influence the water flow. The magnets are located outside the pipeline and their magnetic field is located across the water flow. The external arrangement of magnets simplifies the installation of the magnetic activator and does not require threaded and coupling connections. Accordingly, there is no need to cut the magnetic activator into an existing pipeline. The use of 3D printing allowed creating a compact and easy-to-install housing of the device, suitable for use in domestic conditions.

2. The study showed that the magnesium anode was not able to provide long-term scale protection in hard water conditions, particularly at high heating temperatures. Tests from 2022 to 2023 showed that the magnesium anode provided a passive corrosion protection function, partially reducing scale formation, but its effectiveness was insufficient to fully protect the heating elements. Significant hardness deposits, 2–4 mm thick, formed on the heater surface and tank walls, particularly in the upper part where the water was exposed to the maximum heat. Over time, the magnesium anode deteriorated, reducing its protective function and requiring replacement to maintain its anti-corrosion properties.

3. The conducted studies have shown that the effect of a magnetic field on the hard water flow has a noticeable impact on the processes of scale formation on the surface of heating elements. The magnetic field favors the formation of aragonite, which is less prone to the formation of dense and difficult-to-remove scale deposits compared to calcite. Experimental results confirmed that the use of the magnetic activator reduces the intensity of scale formation on the heating elements, which leads to improved heat exchange and reduced probability of damage to the heating element.

4. As a result of the research carried out, it has been found that as the scale thickness increases, the heat transfer efficiency decreases, resulting in increased power consumption to achieve the required water heating temperature. At a scale thickness of 2–4 mm, the energy consumption reaches 18–27 % as a dense layer of scale prevents normal heat exchange and causes the heating element to overheat. Thus, the results of the study showed that reducing the formation of scale and reducing its thickness can significantly reduce the energy consumption for water heating, as well as extend the life of the electric heater, reducing the risk of its failure due to overheating.

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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