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Experimental Study on the Combined Effect of Electromagnetic and Electrochemical Processes on Descaling and Anticorrosion

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Abstract: In this study, a circulating water experimental system was constructed to investigate the scale inhibition, scale removal, corrosion inhibition, and disinfection effects of industrial circulating water under the combined action of electromagnetic and electrochemical fields. The influence of these effects on water quality parameters and their scale inhibition and corrosion inhibition effects on hanging plate experiments were examined. Qualitative and quantitative analyses of scale samples were conducted using XRD (X-ray diffraction) and SEM (scanning electron microscopy), along with the evaluation of changes in water quality parameters (such as conductivity, hardness, Chemical Oxygen Demand (COD), turbidity, iron ions, and chloride ions) before and after the experiments. The results showed that after 360 h of circulation experiment, at a water temperature of 30 °C, electromagnetic field frequency of 1 kHz, electrochemical scale removal device voltage of 24 V, current of 10 A, and water flow rate of 0.6 m/s, the transformation of calcite to aragonite in $CaCO_3$ scale samples occurred, with a 76.6% increase in aragonite content. Moreover, the conductivity decreased by 11.6%, hardness decreased by 42.0%, COD decreased by 59.7%, turbidity decreased by 48.1%, and chloride and iron ion concentrations decreased by 36.6% and 63.1%, respectively. The scale inhibition efficiency reached 53.8%, surpassing the effects of electromagnetic and electrochemical actions individually. These findings demonstrate that the combined action of electromagnetic and electrochemical fields can effectively enhance scale inhibition, scale removal, corrosion inhibition, and disinfection and algae removal effects.

Keywords: electromagnetic; electrochemical; composite field; SEM; scale removal; corrosion

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1. Introduction

The stable operation of industrial circulating water systems is of paramount importance for ensuring enterprise safety and stable production. However, these systems face numerous challenges such as scaling, corrosion, and biofouling. These issues not only impact the operational efficiency and reliability of the systems but also increase maintenance costs and safety risks. Therefore, adopting effective water treatment methods is crucial to ensure the normal operation and long-term stability of industrial circulating water systems. Researchers have proposed various methods to address these challenges, including physical cleaning, ultrasonic techniques, ion exchange resin methods [1], chemical agents, electrochemical approaches [2], and electromagnetic treatments [3–5]. Each method has its unique advantages and limitations. Physical cleaning is straightforward but may lead to equipment wear; chemical agent methods are widely used but can cause water pollution; ion exchange resin methods are versatile but costly; ultrasonic techniques effectively remove small particles and deposits but have limited applicability; electromagnetic methods are simple to operate and environmentally friendly but have limited scale removal effectiveness; electrochemical approaches exhibit significant scale removal effects and also offer bactericidal and algaecidal properties but may increase energy consumption when treating large volumes of industrial circulating water. Physical cleaning, chemical agent methods, and ultrasonic techniques excel in removing fouling but have limited effectiveness in corrosion protection, disinfection, and algae inhibition. Electrochemical methods demonstrate significant scale removal effects but lack corrosion protection capabilities, while electromagnetic methods exhibit good scale inhibition and corrosion protection but have limited scale removal capabilities. Currently employed methods are insufficient in overcoming the scaling, corrosion, and other challenges faced by industrial circulating water systems. Hence, researchers have begun to investigate whether the synergistic combination of multiple methods can achieve better scale removal and corrosion protection effects [6–8]. Despite the relative scarcity of research on the synergistic effects of electromagnetic and electrochemical techniques compared to other scale removal methods, this area has not received adequate attention. Electromagnetic scale inhibition technology alters the physical and chemical properties of the solution to dissolve more scaling ions in water, thereby inhibiting scale formation. However, over time, as the solution concentration increases, calcium ion concentrations also rise, leading to scale formation. Electrochemical scale removal technology induces redox reactions to precipitate scaling ions at the cathode of electrochemical scale removal devices, resulting in significant scale removal effects. However, electrochemical scale removal devices only operate in the vicinity of the anode and cathode, necessitating multiple devices to treat large volumes of industrial circulating water, thereby increasing energy consumption. While scholars have extensively studied the mechanisms of electromagnetic scale inhibition and electrochemical scale removal, there is still controversy regarding their combined effects on scale inhibition, scale removal, corrosion protection, and bactericidal and algaecidal effects.

In this context, following separate investigations into electromagnetic scale inhibition technology and electrochemical scale removal technology [9], our research team decided to integrate the two and explore whether the synergistic application of electromagnetic and electrochemical techniques in industrial circulating water systems could yield improved scale inhibition, scale removal, and corrosion protection effects. We devised a composite scale removal system for industrial circulating water. The system operates under the following conditions: a water temperature of 30 °C, an electromagnetic field frequency of 1 kHz, an electrochemical descaling device voltage of 24 V, a current of 10 A, and a water flow rate of 0.6 m/s. Firstly, experimental studies were conducted to examine the influence of electromagnetic and electrochemical scale removal techniques on water quality parameters. Subsequently, qualitative and quantitative analyses of scale samples under different scale removal conditions were performed using XRD and SEM. Finally, the amount of scaling before and after hanging plate experiments was calculated, and the corrosion condition was observed to investigate whether their synergistic action could enhance scale inhibition, scale removal, and corrosion protection efficiency. This research not only contributes to a deeper understanding of industrial circulating water treatment technologies but also holds the potential to provide technical support in identifying more efficient methods for industrial circulating water treatment, thereby offering new technological solutions for future industrial applications.

The purpose of the research is to solve the problems of equipment corrosion, pipe scaling, and biological slime in the circulation system in industrial circulating water, which cannot be fully solved by conventional technology. First, electromagnetic scale inhibition and corrosion protection principles are introduced in detail; then the principles of electrochemical water treatment technology are described. At the same time, their advantages and disadvantages are compared. Secondly, to explore new solutions, the experimental platform of industrial circulating water composite scale removal is constructed. Finally, the effectiveness of this method is tested by experimental results.

2. Theoretical Analysis

2.1. Electromagnetic Scale Inhibition and Corrosion Protection Principles

Electromagnetic scale inhibition technology has been widely applied in industries such as steel, power, and pharmaceuticals, exhibiting favorable effects on scale removal, corrosion prevention, and disinfection in circulating cooling water systems. The structural forms primarily include wound and coaxial cavity types. Taking the wound electromagnetic scale inhibition device as an example, its scale inhibition mechanism is illustrated in Figure 1.

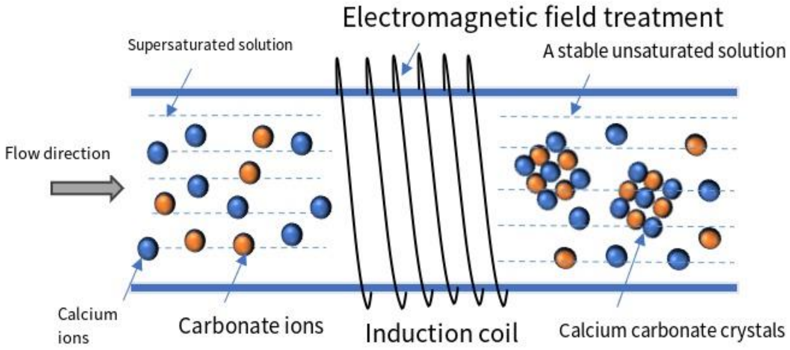


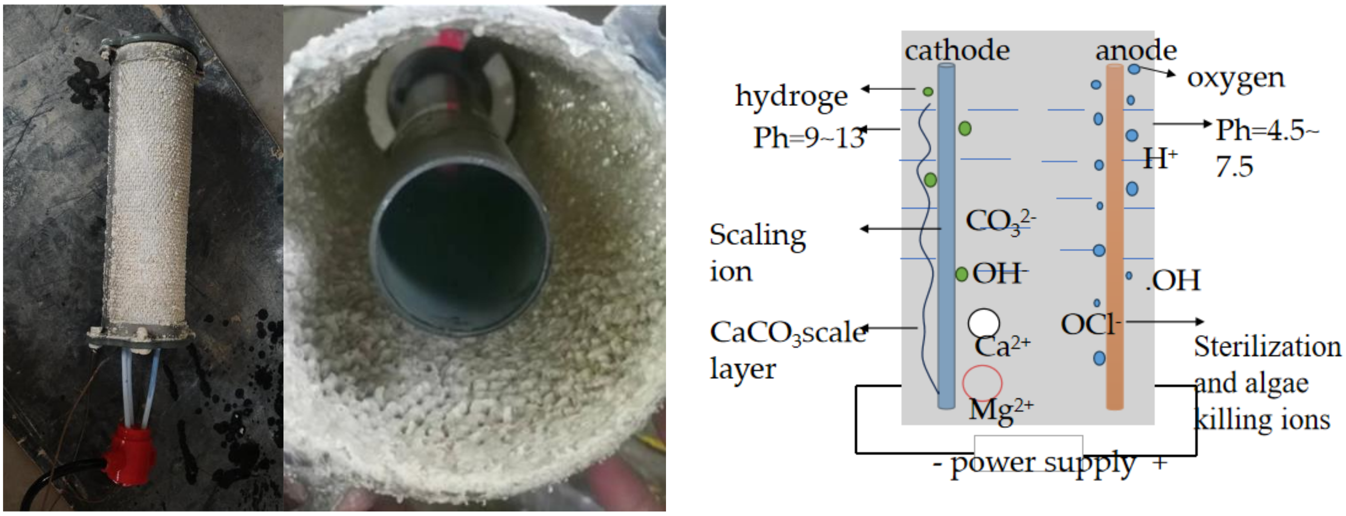
Figure 1. Schematic diagram of electromagnetic scale inhibition technology.

- Scale inhibition principle: During the process of circulating water experiencing electromagnetic fields, water molecules act as dipoles and undergo repeated polarization, leading to distortion, deformation, inversion, and vibration of water molecules. Under the influence of electromagnetic fields, the outer electrons of water molecules are activated, transitioning from lower energy level orbitals to higher energy level orbitals, causing the molecular lattice of scale samples to change from calcite structure to aragonite structure. With the increase in high-frequency vibration and molecular motion, various comprehensive chain like and cluster like macromolecules $(H_2O)_n$ formed in water are decomposed into individual water molecules n (H_2O), ultimately forming relatively stable diatomic water molecules connected by hydrogen bonds. This process enhances the activity and polarity of water, thereby weakening the electrostatic attraction between scaling ions and preventing their aggregation or chemical bonding. At the same time, various positive and negative particles are surrounded by water dipole clusters, no longer moving freely, but oriented along the direction of magnetic field lines, thereby disrupting the conditions for scale formation and achieving the goal of scale inhibition.
- Under the action of electromagnetic fields, water molecules undergo changes. Electromagnetic fields can affect the hydrogen bonding structure of water molecules, leading to the rearrangement of hydrogen bonds between water molecules, thereby changing the physical and chemical properties of water. At the same time, the solubility of oxygen also increases. As the solubility of oxygen increases, reaction occurs between iron rust, active water, and oxygen, forming a dense black oxide film, thereby preventing further corrosion of the pipe wall and achieving the effects of rust removal and rust prevention [10]. During the action of the electromagnetic field, a magnetic field gradient force is generated in pitting corrosion pits, with the maximum magnetic flux density produced at the edge of the pits. The gradient force acts on magnetic materials, attracting erosive ions to move outward, thereby slowing down the pitting corrosion process [11].
- Disinfection and algae elimination principle: Microorganisms generally can only adapt and survive in an electric field strength of 130 eV/m. The electromagnetic field can cause the loss of metabolic function of “repair enzymes” in microbial cells, inhibiting cell activity, thereby disrupting the living biological field of microorganisms and causing the leakage of protoplasm from the cells, leading to death. Simultaneously, a

certain amount of reactive oxygen species ($\cdot OH$, H_2O_2, etc.) can be generated in the water. Reactive oxygen can destroy ion channels of biological cells and accelerate the aging of cell membranes, thus exhibiting strong bactericidal and algaecidal effects.

2.2. Principles of Electrochemical Water Treatment Technology

Electrochemical scale removal technology, as an effective method for eliminating scale in water, can be categorized into automatic and manual scale removal systems. While automatic scale removal saves labor, it requires subsequent treatment due to the high water content in the scale. Conversely, manual scale removal, characterized by its simplicity and convenience, still holds significant importance. The typical representation of manual scale removal is the rat-cage-type scale remover, as shown in Figure 2a. Its principle mainly relies on the electrolysis of water and the adsorption of positive and negative ions by the anode and cathode, respectively, achieving both scale removal and disinfection functions. The schematic diagram of the electrochemical scale removal principle is shown in Figure 2b.



(**a**) (**b**)

Figure 2. (**a**) Physical diagram of squirrel cage descaling machine; (**b**) Principle diagram of electrochemical descaling.

Throughout the process, scale removal primarily occurs in the cathodic region, while the bactericidal and algaecidal effects mainly concentrate in the anodic region.

In the cathodic region, oxidation-reduction reactions and hydrogen evolution reactions generate OH^- ions, rendering the local area alkaline. Chemical reactions such as Equations (1) and (2) accompany this process [12]:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{1}$$

$$2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^- \tag{2}$$

During the hydrogen evolution reaction, numerous bubbles are observed around the scale remover, indicating that hydrogen evolution is the primary reaction generating OH^- ions [13]:

$$CO_2 + 2OH^- \rightarrow {CO_3}^{2-} + H_2O \tag{3}$$

$$HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O \tag{4}$$

As depicted in Equations (3) and (4), the reaction process involves a minor amount of CO_2 reacting with OH^- ions, as well as the reaction of $HCO_3{}^-$ ions moving to the cathode under mass transfer and reacting with OH^- ions to produce $CO_3{}^{2-}$ ions:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow \tag{5}$$

$$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2 \downarrow \tag{6}$$

As shown in Equations (5) and (6), Ca^{2+} and Mg^{2+} ions in water precipitate in crystal form, thereby reducing the solution's hardness to achieve scale inhibition [14].

The main chemical reactions occurring at the anode are:

$$H_2O \rightarrow \cdot OH + H^+ + e^- \tag{7}$$

$$OH \rightarrow 1/2O_2 \uparrow + H^+ + e^- \tag{8}$$

$$O_2 + 2OH^- - 2e^- \rightarrow O_3 + H_2O \tag{9}$$

The anodic region primarily undergoes electrolysis of water reactions, as represented by Equations (7) and (9). Through electrolysis of water and the partial dissolution of oxygen in water, highly oxidizing substances such as ozone (O_3) and hydroxyl radicals ($\cdot OH$) are generated. These strong oxidizing substances oxidize various components within algal and microbial cells, leading to their death [15]. Equation (8) indicates that the reaction produces a large amount of H^+, rendering the cathodic local area acidic.

$$2Cl^- \rightarrow Cl_2 \uparrow + 2e^- \tag{10}$$

$$Cl_2 + H_2O \rightarrow Cl^- + OCl^- + 2H^+ \tag{11}$$

Due to the presence of chloride ions in water, the reaction also generates OCl^-, which exhibits strong oxidative stability. These strong oxidizing substances (such as $\cdot OH$ and OCl^-) oxidize various components within microbial and algal cells, resulting in their death, achieving the effect of disinfection and algaecide [16].

According to the aforementioned principles, both electromagnetic and electrochemical technologies demonstrate unique advantages in circulating water treatment. Electromagnetic technology exhibits good scale inhibition and corrosion resistance effects. However, with the increase in the concentration of mineral ions such as calcium ions with the increase in the concentration ratio of circulating water, the collision probability between calcium ions and carbonate ions also increases. Thus, the formation of calcium carbonate, mainly in the form of calcite, adheres to heat exchange equipment and pipelines. This explains why electromagnetic scale removal initially performs well but weakens over time due to the accumulation of scale. Electrochemical methods also show promising effects in scale removal and disinfection. When the external electric field generated by the electrochemical water treatment system acts on calcium carbonate crystals, the crystals absorb the external electric field and transform it into the internal energy they need, thereby transforming from calcite to aragonite. However, as indicated by Equations (2) and (8), electrochemical scale removal equipment can only affect the surrounding water area. For large-scale industrial circulating water, more electrochemical scale removal equipment is required, which also means an increase in energy consumption, contradicting the green concept of energy conservation and emission reduction proposed by our country. Considering their respective advantages and disadvantages, we attempt to synergistically apply electromagnetic and electrochemical technologies in circulating water treatment. It is hoped that electromagnetic and electrochemical methods can complement each other's deficiencies, thus achieving a more comprehensive and effective scale removal, corrosion inhibition, and disinfection effect. This combined approach opens up new avenues for industrial circulating water treatment technology, providing a reliable solution to enhance water treatment efficiency and equipment lifespan.

3. Experimental Research Design

3.1. Construction of Industrial Circulating Water Composite Scale Removal Experimental Platform

Industrial circulating cooling water systems typically consist of replenishment systems, heat exchange equipment, cooling towers, collection tanks, and circulating water pumps, as depicted in Figure 3a. Accordingly, to investigate the comprehensive effects of electromagnetic fields and electrochemistry on scale prevention, scale removal, corrosion inhibition, and algae inhibition in circulating water systems, a circulating water system consisting of cooling towers, heat exchangers, temperature control devices, electromagnetic scale removal equipment, electrochemical scale removal equipment, water pumps, pipelines, and other essential devices was constructed, as shown in Figure 3b.

(**a**) (**b**)

Figure 3. (**a**) Industrial circulating water cooling water system 1 Water supply pipe; 2 Heat exchanger; 3 Circulating water pump; 4 Cooling tower (**b**) Physical diagram of a small-scale industrial circulating water composite descaling experimental platform 1 Water storage and replenishment tank; 2 Cooling tower; 3 Scaling machine; 4 Valve; 5 Electrical machinery; 6 Heat exchanger; 7 Temperature control device; 8 Electromagnetic device; 9 Power control cabinet.

The electromagnetic scale inhibition equipment is a spin-magnetic energizer developed by the research team. This energizer magnetizes water primarily through the power supply module, applying a certain voltage and specific frequency of pulse signals at the emitting electrode, generating an electromagnetic field between the metal pipeline and the emitting electrode. The electrochemical scale removal equipment adopts a manual cage-type scale remover. The rated voltage of the scale remover is 24 V with a current of 10 A, and the total length of the device is 1 m. The anode rod electrode is made of titanium-based ruthenium-iridium material with a radius of 6 cm. The cathode adopts a stainless steel mesh cover with a radius of 15 cm, and scale ions are deposited on the cathode mesh cover through electrolytic reaction. The water pump used in the circulating water system is model SGR50-7-18, with a rated power of 750 W and a flow rate of 3000 L/h; the electromagnetic flowmeter model is DJLD-DN50, capable of controlling flow rate within the range of 1–2000 L/h, and the water flow pipeline is connected using DN80 seamless steel pipes.

After each experiment, data processing is conducted. Water hardness (expressed as $CaCO_3$), and COD testing are performed using the Lovibond Spectro Direct multiparameter water quality analyzer, with units in mg/L. Turbidity of water solutions is measured using the Orion AQ4500 chromatograph from Thermo Fisher Scientific, chloride (Cl^-) and iron (Fe) ion concentrations are measured using the Qingdao Ruiming online water quality analyzer, with a range of 0–9999 mg/L. The conductivity meter model is HY-EC6.0, with a testing range of 0–2000 µS/cm. XRD analysis is conducted using the Rigaku Ultima IV from Japan, and SEM microscopy is performed using the ZEISS sigma300 from Germany.

3.2. Experimental Design

In previous experiments, circulating water typically consisted of groundwater or was prepared by mixing calcium chloride and sodium bicarbonate in a molar ratio of 1:2. In this experiment, we directly used the reclaimed water from a chemical enterprise in Xinjiang. Reclaimed water is water reused after treatment from various industrial processes, with relatively poor quality. If satisfactory experimental results can be obtained using reclaimed water, it could significantly reduce the expenses for using tap water in industrial circulating water systems for enterprises. Thus, the research findings would have broader applicability and significance. The water quality parameters of reclaimed water are shown in Table 1.

Table 1. Water quality parameters of reclaimed water.

Parameter	Value	Emission Standard	Percentage Deviation	After Reatment	Unit
Conductivity	2008 ± 2	None	0%	1776	µS/cm
Hardness	286.5 ± 1	≤250	14.6%	166	mg/L
Total alkalinity	351 ± 0.5	≤200	75.5%	To be measured	mg/L
Total phosphorus	0.9 ± 0.1	≤1.0	10%	To be measured	mg/L
COD	62.1 ± 0.1	≤60	3.5%	26	mg/L
Turbidity	20.8 ± 0.1	≤5	316%	10.9	NTU
Iron Ion	2.60 ± 0.01	≤1	420%	1	mg/L
Chlorine Ion	365 ± 1	≤250	66%	221	mg/L
Sulfate Ion	105 ± 4.3	None	0%	To be measured	mg/L

According to the national requirements for the discharge standards of industrial circulating cooling water, the water quality parameters of this reclaimed water, including hardness, COD, turbidity, chloride ion concentration, and iron ion concentration, all exceed the national standards. Direct discharge would lead to environmental pollution. If the water can meet the discharge requirements after treatment by water treatment equipment, it would also save the expenses for sewage discharge for the enterprise. In order to fully evaluate the effects of electromagnetic and electrochemical composite scale removal equipment on water quality parameters, we conducted four sets of experiments. Experiment 1 served as the control experiment, Experiment 2 as the electromagnetic experiment, and Experiments 3 and 4 as the electrochemical experiment and electromagnetic + electrochemical experiment, respectively.

In the experiments, we understood that the temperature of circulating water would affect the solubility of calcium carbonate, and the flow rate of circulating water would also affect the deposition of scale. Additionally, parameters such as electromagnetic field frequency and voltage and current of electrochemical equipment would also influence the experimental results. To better explore the effects of electromagnetic and electrochemical, as well as their combined action on scale removal and corrosion inhibition, we assumed other parameters remained unchanged and focused solely on the effects of electromagnetic and electrochemical, as well as their combined action on scale removal and corrosion inhibition. Based on the data obtained from previous experiments and the actual engineering problems in industrial circulating water systems, we chose to use 200 L of reclaimed water in the storage tank for each experiment. The circulating water temperature was set at (30 ± 1) °C, with a flow rate of 1000 L/h (0.6 m/s). The frequency of the electromagnetic scale removal equipment was set to 1 kHz, and the voltage of the electrochemical scale removal equipment was set to 24 V with a current of 10 A. Moreover, two iron hanging plates and stainless steel hanging plates, each sized 70 × 35 × 2 mm with a surface area of 53.2 cm^2, were, respectively, placed in the cooling tower and heat exchanger. The stainless steel hanging plates, possessing better corrosion resistance, were tightly attached to the inner wall surface of the heat exchanger to facilitate better adherence of scale generated in the solution during the experiment. Considering that the formation of scale is a relatively slow process, we selected a longer experimental duration of 360 h for each group. After the experiments concluded, the water used in the experimental system was slowly drained, and the hanging plates were removed, dried, and weighed. Additionally, water quality parameters were measured and recorded.

- Experiment 1—Control Experiment: Under the conditions of a circulating water volume of 200 L, temperature of (30 ± 1) °C, and flow rate of 1000 L/h (0.6 m/s), the scaling and corrosion of circulating water were studied without the use of electromagnetic and electrochemical water treatment equipment, serving as a contrast to the experimental results of the electromagnetic group, electrochemical group, and their combined action.
- Experiment 2—Electromagnetic Group Experiment (EM Group): Keeping the circulating water volume, temperature, and flow rate constant, only the electromagnetic water treatment equipment was activated, with the frequency set to 1 kHz. The changes in water quality parameters and the scaling and corrosion of hanging plates after electromagnetic treatment were observed to study the effects of electromagnetic treatment on scale formation, corrosion, and algae inhibition in circulating water.
- Experiment 3—Electrochemical Group Experiment (EC Group): Keeping the circulating water volume, temperature, and flow rate constant, only the electrochemical water treatment equipment was activated, with the voltage set to 24 V and current to 10 A. The changes in water quality parameters and the scaling and corrosion of hanging plates after electrochemical treatment were observed to study the effects of electrochemical treatment on scale formation, corrosion, and algae inhibition in circulating water.
- Experiment 4—Electromagnetic + Electrochemical Group Experiment (EM + EC Group): Maintaining the circulating water volume at 200 L, temperature at (30 ± 1) °C, and flow rate at 1000 L/h (0.6 m/s), both electromagnetic and electrochemical equipment were activated. The frequency of the electromagnetic water treatment equipment was set to 1 kHz, and the voltage of the electrochemical water treatment equipment was set to 24 V with a current of 10 A. The changes in water quality parameters and the scaling and corrosion of hanging plates after the combined action of electromagnetic and electrochemical treatment were observed to study their effects on scale formation, corrosion, and algae inhibition in circulating water.

During the experiments, it is noteworthy that when measuring the chloride ion concentration in the solution, due to the density of chlorine gas being 2.5 times that of air and easily soluble in water, chlorine ions in the solution would not be removed after being oxidized into chlorine gas. Therefore, a fan was installed above the small cooling tower. Considering site limitations and the hazards of chlorine gas, within the first 180 h of the experiment, we chose to start and stop the fan periodically. After 180 h of the experiment, when the change in chloride ion concentration in the solution was minimal, the fan was continuously operated.

3.3. Experimental Analysis Methods

Upon completion of the experiment, variations in water quality parameters (conductivity, hardness, COD, turbidity) and the weight of hanging plates were recorded. Qualitative and quantitative analysis of scale samples under different scale removal conditions was conducted using XRD and SEM microscopy to assess the scale removal and algae inhibition effects of electromagnetic and electrochemical composite action. Additionally, changes in iron ion and chloride ion concentrations in the solution before and after the experiment were measured, and alterations in the state of iron hanging plates were observed to evaluate the equipment's corrosion inhibition effect.

Following the experiment, stainless steel hanging plates were removed from the heat exchanger, dried at 100 °C for 10 h, and weighed using the LB-C electronic balance from Changzhou Lanbao Co., Ltd., China Changzhou Lanbao Company (precision: 0.001 g). The scale removal rate η was calculated using the formula [17]:

$$\eta = \left(1 - \frac{m_1 - m_1^{'}}{m_2 - m_2^{'}}\right) \tag{12}$$

where (m'_1) and (m_1) represent the masses of the stainless steel hanging plates in the heat exchanger before and after the experiment in the experimental group, respectively, and (m'_2) and (m_2) represent the masses of the stainless steel hanging plates in the heat exchanger before and after the experiment in the control group, respectively.

The relationship between iron ion concentration and corrosion rate was determined using the weight loss method for hanging plates and corrosion rate measurement in the solution. The equation relating iron ion concentration to corrosion rate is as follows [18]:

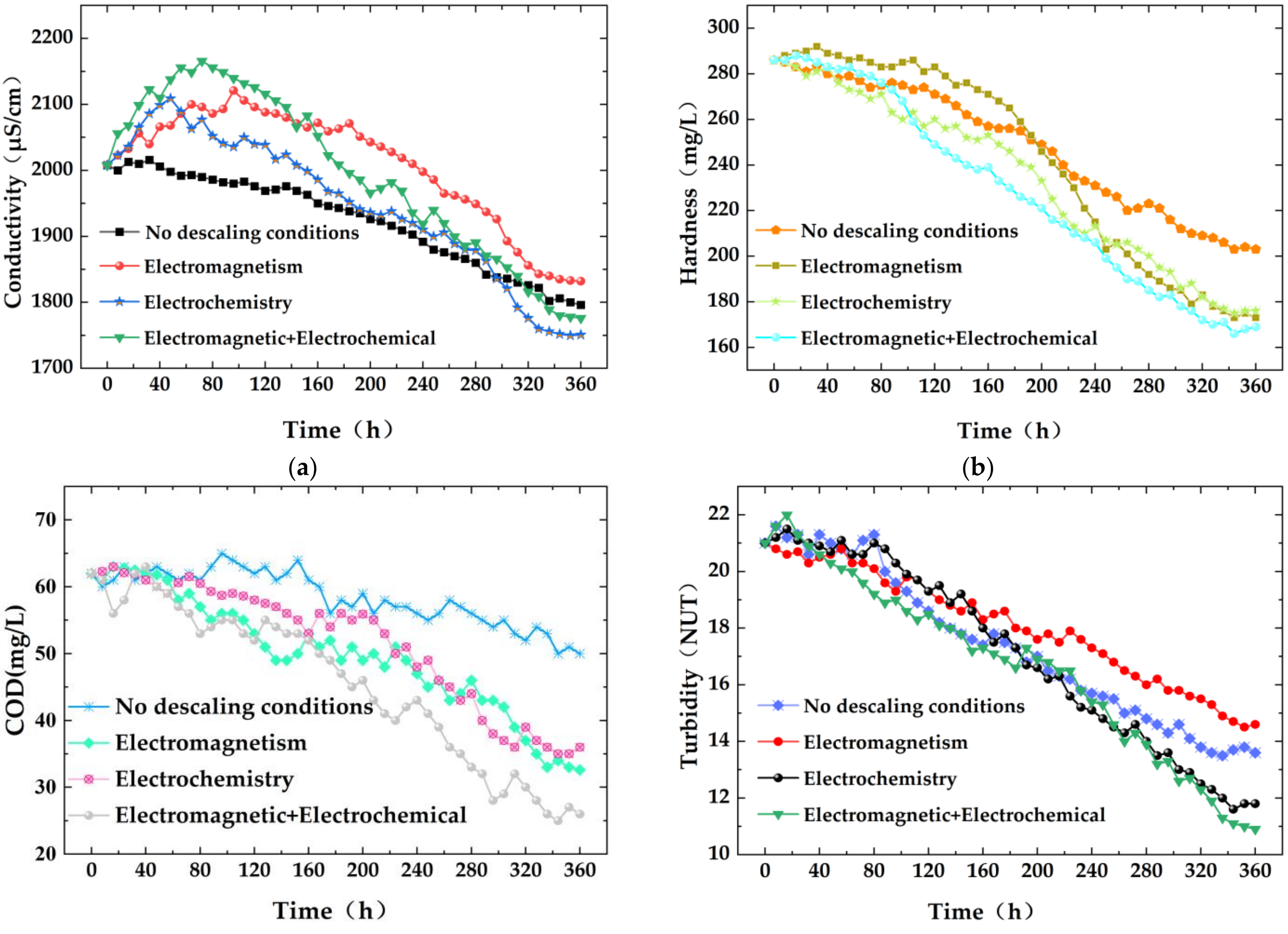
$$v = \frac{(C_1 - C_0)V_t \times 8.76 \times 10^4}{st\rho n} \tag{13}$$

v: Corrosion rate, mm/a;
C_0: Iron ion concentration in the solution before corrosion test, g/L;
C_1: concentration of iron ions in the solution after corrosion test, g/L;
V_t: Total volume of corrosion solution, L;
s: Hanging surface area, cm^2;
t: Corrosion time, h;
ρ: The density of the test piece material, g/cm^3;
n: The number of test pieces hung in the container used for each corrosion test in the experiment.

4. Discussion of Experimental Results

4.1. Change Rate of Water Quality Parameters under Different Descaling Conditions

Water quality parameters are key indicators for evaluating the quality of water, directly affecting the applicability and safety of water. In the process of circulating water treatment, electromagnetic fields and electrochemical methods have a direct impact on water quality parameters, including solution conductivity, hardness, COD, and turbidity. During the experiment, the data was tested every 8 h. The changes in the water quality parameters of the circulating water with the experimental time are shown in Figure 4. The change rate (percentage decrease) of various water quality parameters of the circulating water under different descaling conditions is shown in Table 2.



(**a**) (**b**) (**c**) (**d**)

Figure 4. Variations of various water quality parameters under different decontamination conditions. (**a**) Conductivity, (**b**) Hardness, (**c**) COD, (**d**) Turbidity. Electromagnetic frequency: The experimental conditions are: 1 kHz; Electrochemical voltage: 24 V, Current: 10 A; Temperature: 30 °C; Water flow velocity: 0.6 m/s; Duration: 360 h.

Table 2. The decline rate of various water quality parameters under different descaling conditions.

No.	Descaling Condition	Conductivity	Hardness	COD	Turbidity	Chlorine Ion	Iron Ion
1	None	10.6%	29.1%	19.6%	35.7%	2.7%	7.6%
2	EM	8.8%	39.5%	47.4%	31.0%	30.9%	69.2%
3	EC	12.8%	38.8%	43.5%	44.8%	25.8%	6.5%
4	EM + EC	11.6%	42.0%	59.7%	48.1%	36.6%	63.1%

The experimental results depicted in Figure 4a reveal that both magnetic treatment and electrochemical treatment induce an initial increase followed by a subsequent decrease in the conductivity of the solution compared to the control experiment. On one hand, magnetic treatment enhances the hydrogen bonding between water molecules, resulting in the formation of more water clusters and reinforcing the hydration of ions in the solution. This phenomenon leads to a decrease in excessive calcium carbonate crystallization and subsequently increases the conductivity of the solution.

On the other hand, the enhanced activity and solubility of water molecules increase the solubility of substances like calcium carbonate in water, thereby enhancing the conductivity of the solution [19]. In the electrochemical experimental group, during the process of oxidation reduction, a large amount of H^+, OH^-, and other ions are generated in the solution, leading to an increase in the solution conductivity. However, as the experiment progresses, scaling ions precipitate from the solution, causing a decline in the solution conductivity [20]. Around 200 h into the experiment, the rate of decrease in conductivity accelerates due to the calcium carbonate crystals that have precipitated acting as crystal seeds. This accelerates the crystallization of calcium carbonate, leading to a faster precipitation of scaling ions and consequently a rapid decline in solution conductivity. Notably, electrochemical descaling exhibits the most effective decrease in solution conductivity, with a reduction rate of 12.8%.

From Figure 4b, it can be observed that in the control group, the concentration of calcium ions gradually decreases to stability with minimal variation, whereas in the electromagnetic group, the concentration of calcium ions shows a slight increase before declining to stability. This is attributed to the electromagnetic anti-scaling technology, wherein the electromagnetic field increases the solubility of the solution, resulting in a slight increase in the concentration of calcium ions. However, under the influence of the electromagnetic field, calcium ions and carbonate ions are accelerated due to the Lorentz force, increasing the chances of collision and thus accelerating crystallization, leading to a decrease in the concentration of calcium ions in the solution. In the electrochemical experimental group, the trend of decreasing calcium ion concentration varies from rapid to slow. This may be because, initially in the reaction, the cathode surface is relatively clean, exhibiting the highest electrochemical activity, and scale can quickly deposit on the cathode surface to form a negatively charged $CaCO_3$ layer, providing numerous nucleation sites, which attract Ca^{2+} electrostatically. However, as the reaction progresses, the majority of the cathode surface is occupied by scale deposits, reducing the effective deposition area, while the thickening of the $CaCO_3$ deposition layer blocks the ion transport channels, hindering the effective combination of Ca^{2+}, HCO_3^-, etc., with OH^- ions, leading to a decrease in hardness removal efficiency and a plateauing trend [21,22].

COD (Chemical Oxygen Demand) is a crucial indicator used to assess the organic content in water or solution, reflecting the amount of chemical oxidant required for organic matter in water under certain conditions. From Figure 4c, it can be observed that in the electromagnetic experimental group, the COD content of the solution shows a slow decline. This is because the electromagnetic field alters the activity of water molecules, increasing the number of water molecules and charged particles passing through the semi-permeable membrane, resulting in an increase in the water molecules inside microbial cells. This damages the cell membranes of microorganisms. Additionally, under electromagnetic action, active oxygen species such as OH^- and H_2O_2 are generated in water, disrupting bacterial metabolism, ultimately achieving microbial eradication. At specific frequencies, the electromagnetic field causes resonance with oversaturated water molecules, leading to the rupture and shedding of bacterial and other microbial cell walls, promoting the decomposition of organic molecules into smaller molecules or conversion into inorganic substances [23], thereby reducing the COD concentration of the solution. In the electrochemical experimental group, the oxidation-reduction process of electrochemistry leads to the death and dissolution of organic matter such as bacteria and algae, thereby reducing the COD concentration of the solution.

The degree to which suspended particles hinder the passage of light through water is termed turbidity. In the circulating water under the experimental conditions of this chapter, calcium carbonate scale is the main source of suspended solids. When the circulating water containing suspended solids flows rapidly, it may cause erosion and corrosion of low-hardness heat exchange surfaces; when the circulating water containing suspended solids flows slowly, it is prone to sedimentation, leading to sub-scale corrosion. The water used in the experiment is moderately turbid. From Figure 4d, it can be seen that in the initial stages of the experiment (0–80 h), there is minimal change in the turbidity of the solution, but after some time, scaling ions in the circulating water precipitate as calcium carbonate crystals, leading to a decrease in turbidity of the solution. It can be observed that after electromagnetic treatment, the turbidity of the solution is higher compared to the control group, indicating more suspended calcium carbonate in the circulating water after electromagnetic treatment and less scaling inside the heat exchange equipment and pipelines [24].

4.2. Changes in the Quality of Stainless Steel Hanging Plates inside Heat Exchangers

For each experiment, a stainless steel hanging plate is polished clean, weighed, and placed in the heat exchanger. After the experiment is completed, it is taken out, dried, and weighed. The scale inhibition rate under different descaling conditions is calculated using Equation (12), as shown in Table 3:

Table 3. Scale inhibition rates under different descaling conditions descaling conditions.

No.	Descaling Condition	Initial Weight (g)	Final Weight (g)	Change in Weight (g)	Scale Inhibition Rate
1	Control Group	41.526	41.539	0.013	0
2	EM	36.528	36.536	0.008	38.5%
3	EC	40.366	40.463	0.010	23.1%
4	EM + EC	39.231	39.273	0.006	53.8%

According to the anti-scaling rates shown in Table 3, it can be observed that electrochemical treatment performed the worst, followed by the effect of the electromagnetic field, while the combination of both exhibited the most significant effect. This result can be explained in several aspects: firstly, the electromagnetic field alters the physicochemical properties of the solution, enhancing its solubility, thus promoting the dissolution of more scaling ions into the water, thereby inhibiting scaling. Secondly, the electromagnetic field can also alter the crystal structure, transforming the originally hard aragonite into the softer calcite, making it easier to be washed away by the flow of water. According to the principle of electrochemical descaling, it is known that electrochemical descaling involves the deposition of scaling ions from the solution onto the cathode, thereby reducing precipitation within the heat exchange equipment and pipelines. This indicates that both the electromagnetic field and electrochemical methods can alter the nature of scaling ions in water, disrupting the original precipitation–dissolution equilibrium, and causing them to move towards dissolution into ions. The combined effect of the two can more rapidly promote the movement of this equilibrium [6].

4.3. Effects of Different Descaling Conditions on Calcium Carbonate Crystals

We know that $CaCO_3$ commonly exists in two crystal forms: the hard aragonite and the softer calcite. The process of $CaCO_3$ crystal formation includes the generation of nuclei and the growth of crystals. Nucleation is the cause of fouling, while crystal growth leads to deposition. Therefore, studying only the macroscopic amount of scaling on the hanging pieces is not sufficient to explain the anti-scaling and anti-corrosion effects. In order to better evaluate the anti-scaling and anti-corrosion effects of electromagnetic and electrochemical methods, as well as their combined effects, we investigated the influence of different descaling conditions on $CaCO_3$ fouling from a microscopic perspective. We used XRD for qualitative and quantitative analysis of $CaCO_3$ fouling under different descaling conditions, and SEM electron microscopy for morphology observation of the fouling samples. Figure 5 shows the XRD spectra of $CaCO_3$ fouling samples under different descaling conditions, where C represents calcite and A represents aragonite. Figure 6 shows the SEM images of $CaCO_3$ fouling samples under different descaling conditions. Using XRD analysis software jade6.5, we performed qualitative and quantitative analysis of $CaCO_3$ fouling samples by fitting the spectra and calculating the mass fractions of aragonite and calcite, as shown in Table 4 for the XRD quantitative analysis of $CaCO_3$ fouling samples under different descaling conditions.

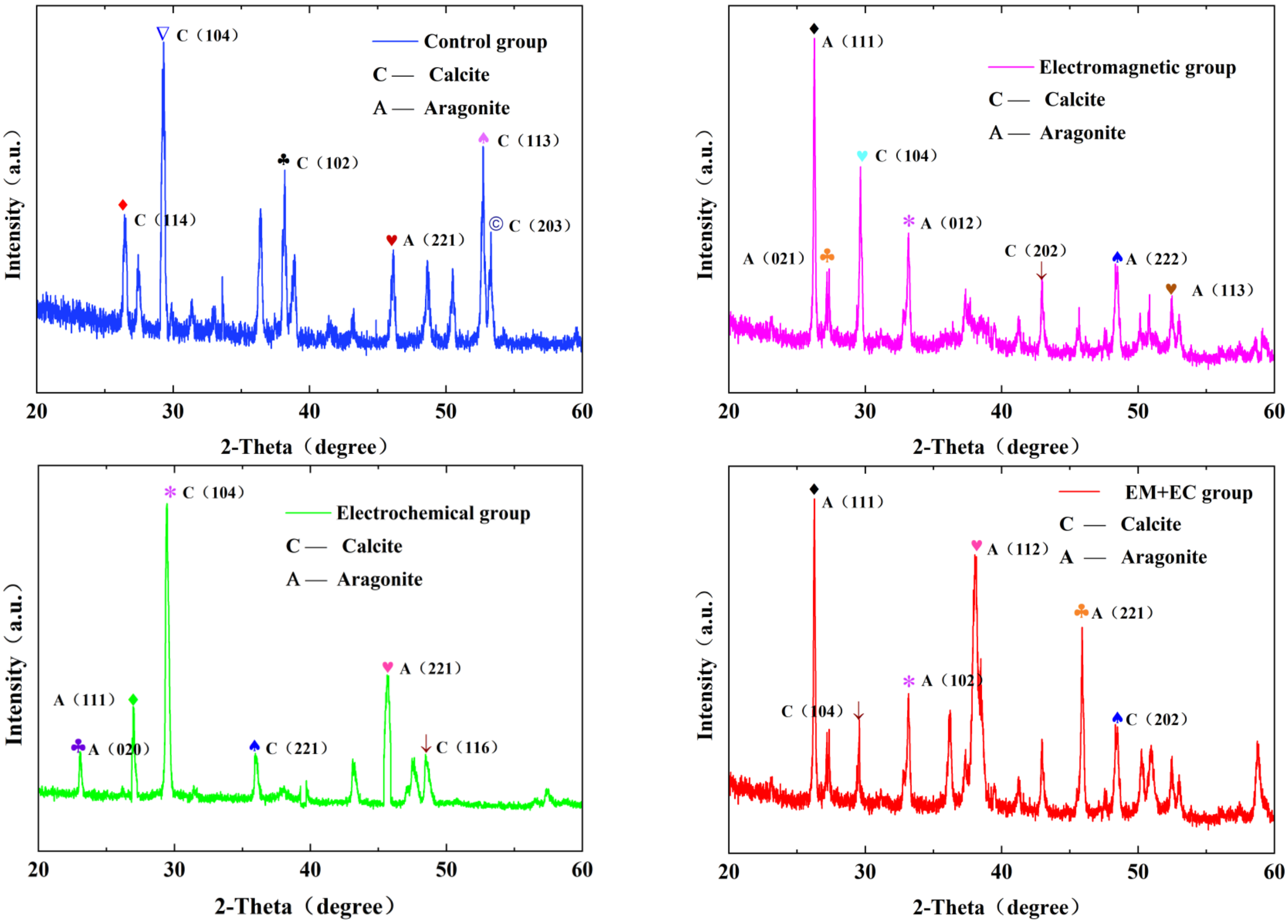


Figure 5. XRD spectra of $CaCO_3$ scale samples under different descaling conditions.

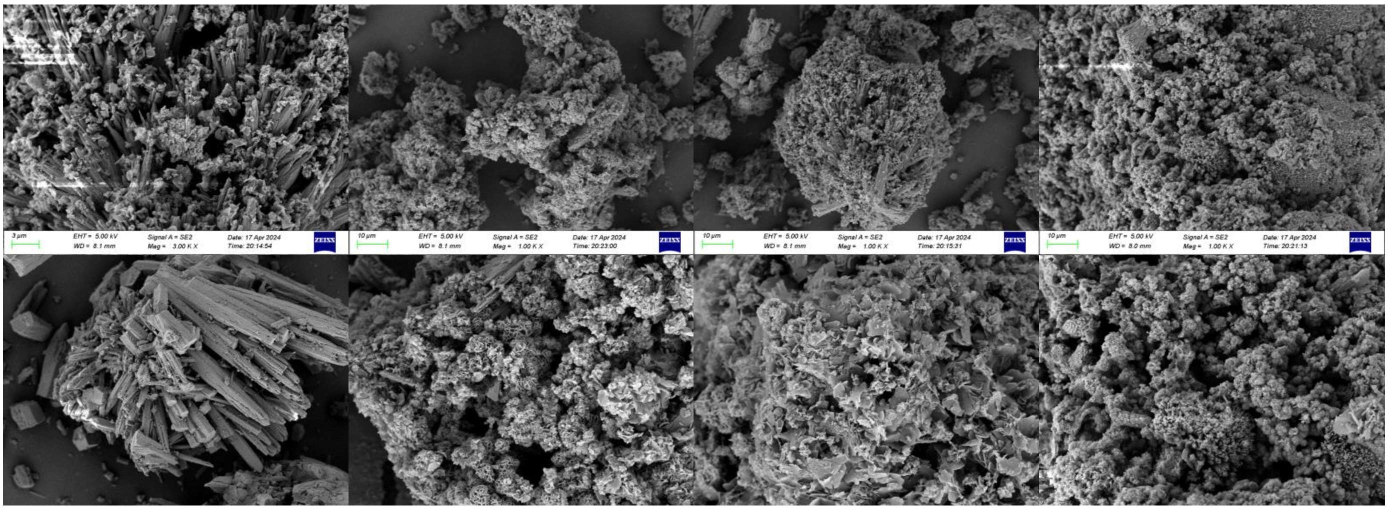

(**a**) (**b**) (**c**) (**d**)

Figure 6. SEM images of $CaCO_3$ scale samples under different descaling conditions. (**a**) Control group; (**b**) Electromagnetic group; (**c**) Electrochemical group; (**d**) EM + EC group.

Table 4. XRD quantitative analysis of $CaCO_3$ scale samples under different descaling conditions.

No.	Descaling Condition	Calcite Mass Fraction	Dolomite Mass Fraction (%)
1	Control Group	92.8%	7.2%
2	EM	30.7%	69.3%
3	EC	46.2%	53.8%
4	EM + EC	16.2%	83.8%

Through the analysis of Figure 5 and Table 4, it is evident that after electromagnetic and electrochemical treatments, the calcium carbonate ($CaCO_3$) crystals in the fouling samples undergo a transformation from the hard calcite to the softer aragonite. Moreover, the synergistic effect of electromagnetic and electrochemical treatments is most pronounced. Compared to the control group, the combination of electromagnetic and electrochemical treatments decreases the calcite content in $CaCO_3$ fouling samples from 92.8% to 16.2%, while increasing the aragonite content from 7.2% to 83.8%, resulting in a growth of 76.6%. This growth is higher than that observed in the electromagnetic group (62.1%) and the electrochemical group (46.6%).

From Figure 6, untreated scale samples exhibit a cubic shape, often appearing as tetrahedral or prismatic calcite forms, densely clustered together with high structural density. These structures are prone to deposition on the walls of pipes or surfaces of heat exchange equipment, affecting the normal operation of the equipment. In contrast, scale samples treated with electromagnetic fields exhibit regular features, typically appearing as elongated or similar-shaped aragonite forms, with a relatively sparse and loose structure that is easily flushed away by water flow. This structure reduces the ability of scale to deposit on the walls of pipes or equipment surfaces, aiding in the reduction in scale formation and accumulation, thereby improving the operational efficiency and reliability of the equipment [20]. For the electrochemical treatment group, there is the formation of relatively regular and smaller-sized calcite, with some aragonite produced as well. This also facilitates better adsorption of calcium carbonate crystals on the cathode surface, where the calcium carbonate crystals act as nucleation sites, causing more calcium carbonate crystals to precipitate rapidly [18]. With electrochemical action, the free energy of calcium carbonate crystal nucleation continuously increases, leading to the transformation of calcite into aragonite, resulting in an increase in aragonite content. Under the combined action of electromagnetic and electrochemical treatments, calcium carbonate crystals predominantly precipitate as the softer aragonite.

4.4. Corrosion of Iron Hanging Pieces in the Cooling Tower

Factors affecting metal corrosion include pH value, temperature, flow rate, chloride ion concentration, and iron ion concentration, among others, with chloride and iron ion concentrations being particularly crucial [25]. To assess the effectiveness of electromagnetic and electrochemical methods in corrosion prevention and whether their synergistic action can enhance operational efficiency, we employed the weight loss method to determine the iron ion concentration and corrosion rate in the solution. Results indicate that higher iron ion concentrations in the solution correspond to faster corrosion rates. Chloride ion concentration plays a significant role in metal corrosion, as an increase in chloride ion concentration leads to an increase in corrosion severity. Therefore, reducing chloride ion concentration has a positive effect on corrosion prevention [26]. The changes in iron ion and chloride ion concentrations in the solution, as well as the state of the iron hanging pieces, were observed before and after the experiments to evaluate the equipment's corrosion prevention effectiveness. The changes in the hanging pieces under different descaling and corrosion prevention conditions are shown in Figure 7, while the variations in iron ion and chloride ion concentrations in the solution are depicted in Figure 8.


(**a**) (**b**) (**c**) (**d**)

Figure 7. Corrosion situation of hanging plates under different descaling conditions Electromagnetic frequency: The experimental conditions are: 1 kHz; Electrochemical voltage: 24 V, Current: 10 A; Temperature: 30 °C; Water flow velocity: 0.6 m/s; Duration: 360 h. (**a**) Control group; (**b**) EM group; (**c**) EC group; (**d**) EM + EC group.

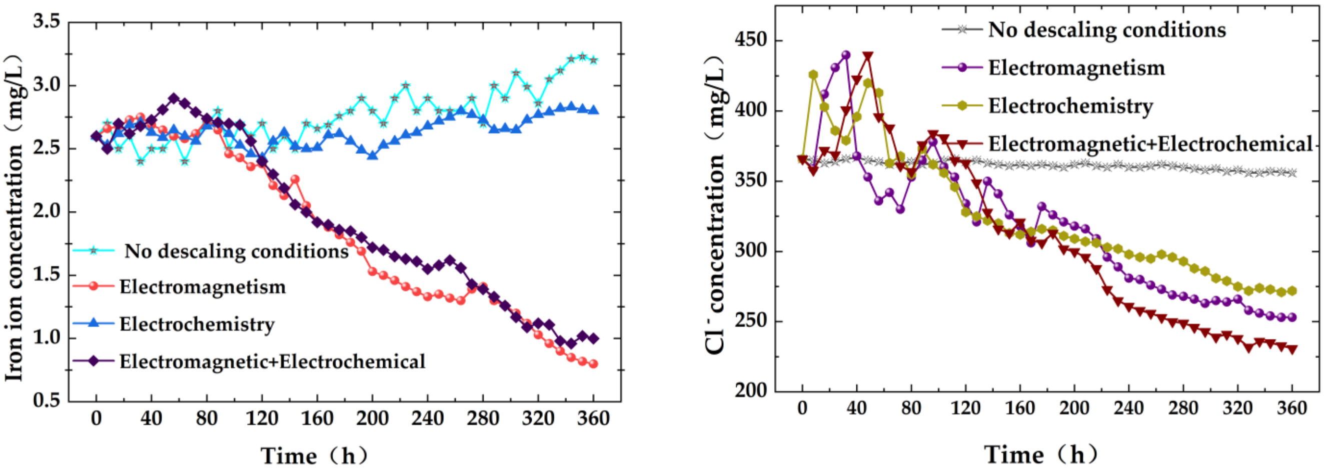


Figure 8. Changes in iron and chloride ion concentrations under different descaling conditions.

From Figure 7, it is evident that the control group without any descaling treatment exhibited more severe corrosion. The main reason for this is that the water source used in the experiment is moderate water with poor quality, containing high concentrations of chloride ions and iron ions. In comparison, the electromagnetic group showed a significant anti-corrosion effect, while the electrochemical group demonstrated a moderate anti-corrosion effect. It is noteworthy that the combination of electromagnetic and electrochemical methods also showed some corrosion, but compared to the control group, the degree of corrosion was less severe. According to the data in Figure 8, the application of an electromagnetic field can reduce the concentration of iron ions in the solution. The effect of electrochemical methods on the concentration of iron ions in the solution is less stable, showing an overall increasing trend. However, the combined action of electromagnetic and electrochemical methods demonstrated the best effect in reducing the concentration of iron ions. This is because the electromagnetic field promotes the generation of ferric oxide in the solution, thereby reducing the concentration of iron ions and protecting the equipment and pipelines from corrosion. However, in electrochemical experiments, the occurrence of numerous oxidation-reduction reactions can lead to temporarily acidic or alkaline conditions in localized areas, promoting corrosion of metal equipment and pipelines, and increasing the concentration of iron ions in the solution [10,11]. The variation in chloride ions is closely related to the operation of the fan. When the fan is turned on, it can be observed that both electromagnetic and electrochemical actions effectively remove chloride ion concentrations from the solution, and their combination exhibits even better removal efficiency. The corrosion rates calculated using Equation (13) under different conditions and at different times are shown in Figure 9. Negative values indicate a relative decrease in iron ion concentration compared to the initial concentration at this time, indicating that corrosion is not significant at this moment.

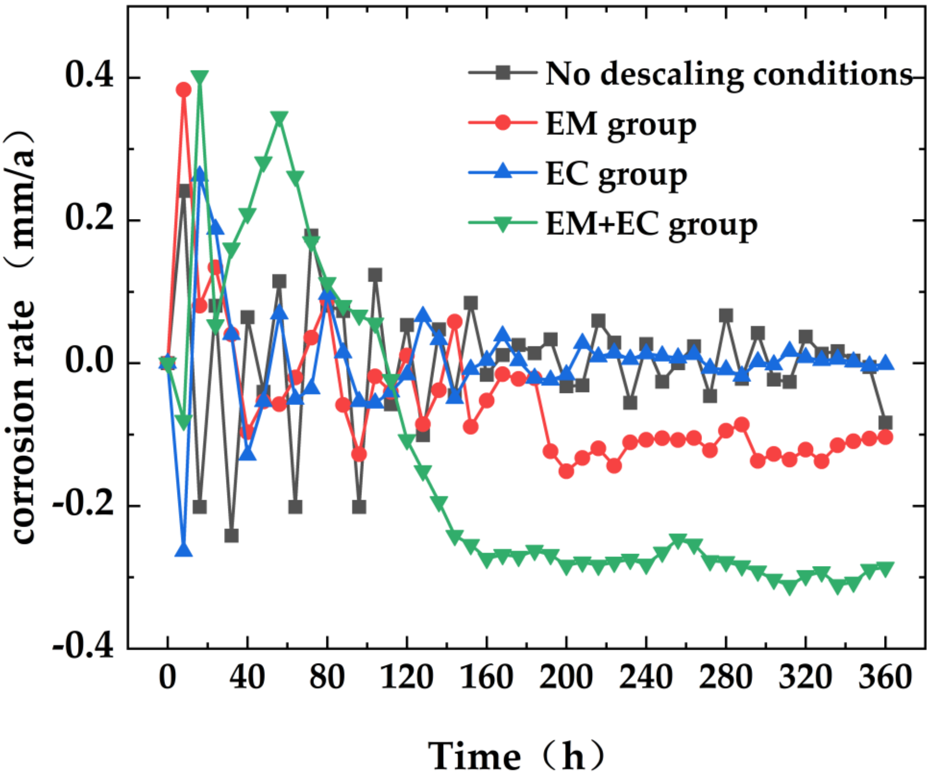


Figure 9. The variation of corrosion rate under different descaling conditions.

5. Conclusions

1. The experiments above verify that the combined action of electromagnetic and electrochemical methods has a good anti-scaling and descaling effect. Qualitative and quantitative analysis of $CaCO_3$ fouling samples was conducted under different descaling conditions using XRD, and the morphology of fouling samples was observed by SEM electron microscopy. It was found that the combined action of electromagnetic and electrochemical methods reduced the calcite content in $CaCO_3$ fouling samples from 92.8% to 16.2%, while increasing the aragonite content from 7.2% to 83.8%, resulting in a growth of 76.6%.
2. Considering the changes in water quality parameters, hanging piece quality, and corrosion conditions, we conclude that the combined anti-scaling and anti-corrosion effect is significantly superior to individual applications. Under specific conditions, such as a water temperature of 30 °C, electromagnetic field frequency of 1 kHz, electrochemical descaling equipment voltage of 24 V, current of 10 A, and water flow rate of 0.6 m/s, the combined action of electromagnetic and electrochemical methods resulted in a decrease in solution conductivity by 11.6%, hardness by 42.0%, COD by 59.7%, turbidity by 48.1%, chloride ion concentration by 36.6%, and iron ion concentration by 63.1%. The composite anti-scaling efficiency reached 53.8%, demonstrating excellent anti-scaling, descaling, bactericidal, and algal inhibition effects.

3. The synergistic effect of electromagnetism and electrochemistry not only solves the problem of poor scale inhibition effect caused by long-term operation of electromagnetic scale inhibition technology, but also solves the problem of poor scale removal effect of electrochemical scale removal technology on pipelines and heat exchange equipment.

6. Future Work Suggestions

1. Considering that scaling and corrosion processes require a considerable amount of time, we extended the experimental duration and conducted data checks every 8 h. However, this may lead to the inability to detect short-term fluctuations in the data. Therefore, future work will involve conducting more experiments to shorten the measurement time and improve data stability.
2. Given the potential harm of chloride ions to metal equipment and pipelines, and the limited effectiveness of electromagnetic anti-scaling and electrochemical descaling technologies in removing chloride ions, along with restrictions on fan usage, we will further research methods for removing chloride ions from industrial circulating water.

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