

Article

Water Quality Analysis of a 300 Mvar Large-Scale Dual Internal Water Cooling Synchronous Condenser External Cooling System and Exploration of Optimal Water Treatment Agent Dosage at Different Temperatures

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Abstract: The external cooling water system of a 300 Mvar dual internal water cooling synchronous condenser at a certain ultra-high voltage converter station continued to exhibit significant scaling and corrosion, even with regular addition of scale and corrosion inhibitors. To solve this problem, the external cooling water of the synchronous condenser was sampled and tested periodically, with the main test items including conductivity, pH value, turbidity, hardness, alkalinity, and other water quality parameters directly related to corrosion and scaling. The trends of these parameters over time were also analyzed. The results showed that as the operation time increased, the cooling water became concentrated during multiple circulation cycles, and the various dissolved or suspended substances underwent a certain degree of enrichment. However, the addition of scale and corrosion inhibitors did not dynamically adjust according to the changes in water quality, and there was always an excessive dosage. Thus, using the external cooling water as the experimental sample, static scale inhibition tests and rotating coupon corrosion tests were conducted to evaluate the scale and corrosion inhibition performance of the commercial AS-582 scale and corrosion inhibitor used at this ultra-high voltage converter station under different conditions. Considering the more obvious corrosive tendency of this water sample, the focus was on testing its corrosion inhibition performance. When the dosage was 600 ppm, the scale inhibition effect was optimal, with an inhibition rate of 92.15%. The corrosion inhibition effect of this scale and the corrosion inhibitor were significantly related to water temperature. At 25 °C, when the dosage was 500 ppm, the corrosion inhibition effect was optimal, with an inhibition rate of 86.79%. However, when the temperature increased to 40 °C, the corrosion inhibition effect under each dosage was significantly worse, unable to meet the requirements, and the use of other corrosion inhibitors in combination was necessary. This work will provide a reference for the scientific use of scale and corrosion inhibitors.

Keywords: compensator; external cooling water; water quality analysis; corrosion and scale inhibition; optimal dosing



Citation: Gu, X.; Xu, Y.; Wu, Y.; Yang, L.; Zhang, J.; Chen, X.; Zhou, Z.; Fan, P.; Gao, Y.; Ji, Q.; et al. Water Quality Analysis of a 300 Mvar Large-Scale Dual Internal Water Cooling Synchronous Condenser External Cooling System and Exploration of Optimal Water Treatment Agent Dosage at Different Temperatures. *Water* **2024**, *16*, 3158. <https://doi.org/10.3390/w16223158>

Academic Editor: Antonio Zuorro

Received: 15 June 2024

Revised: 18 July 2024

Accepted: 19 July 2024

Published: 5 November 2024



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1. Introduction

With the rapid development of the national economy, the demand for electricity has increased rapidly. As a dynamic reactive power compensation device, the synchronous condenser is an essential component for maintaining the stable operation of the power grid system, with the function of providing or absorbing reactive power to the power system, which can effectively ensure the normal operation of the power grid and electrical

equipment [1–3]. However, during the operation of the synchronous condenser, a large amount of heat will be generated, which, if not dissipated in time, will affect the normal operation of the equipment [4]. Therefore, ensuring the normal and stable operation of the external cooling water system of the synchronous condenser is an important part of maintaining national power safety [5,6].

Due to the large number of devices that make up the external cooling water system of the synchronous condenser, the complex structure, and the open-system nature, its operating status is highly variable [7]. In daily operation, if the water quality monitoring and treatment of the external cooling water are not properly carried out, problems such as scaling, corrosion, and algae growth may occur in the external cooling water system, which seriously affects the heat transfer efficiency of the equipment [8,9]. In severe cases, the synchronous condenser may have to shut down due to ineffective cooling, affecting the safety and stability of the transmission system. The three major problems of scaling, corrosion, and algae growth have long plagued the power industry. In most cases, the method of adding scale inhibitors, corrosion inhibitors, and biocides to the external cooling water system is adopted to ensure its normal operation [10–12]. However, due to the lack of a systematic understanding of the actual scale and corrosion inhibition effects of water treatment chemicals under different conditions, there are often problems such as unreasonable selection of water treatment chemicals and dosages, or excessive dosing, which leads to unsatisfactory scale and corrosion inhibition effects or exceeding the discharge standards of pollutants [13].

The problems of scaling, corrosion, and algae growth are directly related to the water quality of the cooling water [14]. Therefore, a key measure to achieve the safe and reliable operation of the synchronous condenser cooling water system is to comprehensively monitor and detect the cooling water quality and to reasonably carry out operational control based on changes in water quality [15,16]. Therefore, we periodically collected samples of the external cooling water of a 300 Mvar dual internal water cooling synchronous condenser at a certain ultra-high voltage converter station and tested the water quality parameters directly related to scaling and corrosion. We analyzed in detail the changing trends of these water quality parameters over time and established the relationship between these water quality parameters and scaling and corrosion based on the actual situation of the external cooling water system. This can not only help predict the changes in water quality in the external cooling water system and carry out key monitoring and detection but also help predict the tendency of scaling and corrosion in the external cooling water system based on the water quality situation and carry out more accurate operational control. Based on the above work, we evaluated the scale and corrosion inhibition performance of the commercial AS-582 scale and corrosion inhibitor used at this ultra-high voltage converter station and optimized the dosing plan for different operating conditions. This work will provide a reference for the selection of water treatment scales and corrosion inhibitors in the external cooling water system, to achieve precise dosing, reduce the cost of drugs, and avoid environmental pollution.

2. Materials and Methods

2.1. Water Quality Analysis

The water quality samples were taken from the external cooling water of a 300 Mvar dual internal water cooling synchronous condenser. Random sampling was conducted over a period of three years, involving multiple months and seasons, for a total of 14 samples. It can best illustrate the changes in water quality of the external cooling water system. The water quality parameters of the samples were detected using instruments such as the UV-visible spectrophotometer (UV-2550, Shimadzu, Nakagyo-ku, Kyoto, Japan), ICS-90A ion chromatograph (Shine, Qingdao, China), and 716 DMS automatic potentiometric titrator (Hanon, Jinan, China). The tested parameters include conductivity, turbidity, pH value, hardness, calcium ion (Ca^{2+}) concentration, magnesium ion (Mg^{2+}) concentration,

alkalinity, bicarbonate ion (HCO_3^-) concentration, chloride ion (Cl^-) concentration, and sulfate ion (SO_4^{2-}) concentration.

2.2. Water Treatment Agent

The commercial corrosion and scale inhibitor AS-582 (Zhongjiang Co., Ltd., Foshan, China) is composed of a combination of polymer compounds, carbon steel corrosion inhibitors, and copper corrosion inhibitors. Its main components are Acrylic Acid-2-Acrylamido-2-Methylpropane Sulfonic Acid Copolymer (AA/AMPS) (Zhongjiang Co., Ltd., Foshan, China), 1-Hydroxy Ethylidene-1,1-Diphosphonic Acid (HEDP) (Zhongjiang Co., Ltd., Foshan, China), and 2-Phosphonobutane-1,2,4-Tricarboxylic Acid (PBTC) (Zhongjiang Co., Ltd., Foshan, China). AS-582 has good chelating and dispersing effects on calcium carbonate, calcium sulfate, calcium phosphate, etc., and has good corrosion inhibition effects on carbon steel and copper. AS-582 is mainly used for corrosion and scale inhibition in circulating cooling water systems, with a good corrosion inhibition effect and strong scale inhibition ability.

2.3. Static Scale Inhibition Tests

In a 500 mL volumetric flask, 250 mL of water was added. A certain volume of calcium chloride standard solution was added to make the amount of Ca^{2+} 120 mg. A certain amount of water treatment agent was added and shaken well. 20 mL of borate buffer solution was added and shaken well. A certain volume of sodium bicarbonate standard solution was slowly added to make the amount of HCO_3^- 366 mg. Water was added to dilute the mark and shaken well. The solution was kept in an 80 °C constant temperature water bath for 10 h, then filtered while hot. The remaining Ca^{2+} content in the filtrate was titrated using an EDTA standard solution. Finally, the formulas below were used to calculate the scale inhibition rate under the experimental conditions [17].

The formula for calculating the mass concentration of Ca^{2+} (Y , mg/mL) and the scale inhibition rate (R , %) are as follows:

$$Y = \frac{MV_1C_{\text{EDTA}}}{V} \quad (1)$$

$$R = \frac{Y_2 - Y_1}{Y_0 - Y_1} \times 100\% \quad (2)$$

where M is the molar mass of Ca^{2+} (g/mol), V_1 is the volume of EDTA standard solution consumed (mL), C_{EDTA} is the concentration of EDTA (mol/L), V is the volume of the filtrate (mL), Y_0 is the initial Ca^{2+} mass concentration (mg/L), Y_1 is the Ca^{2+} mass concentration after blank experiment (mg/L), and Y_2 is the Ca^{2+} mass concentration after experiment with inhibitor (mg/L).

2.4. Rotating Coupon Corrosion Tests

External cooling water (1 L) from the 300 Mvar dual internal water cooling synchronous condenser was added to a beaker, and a certain amount of water treatment agent was added. A rotating shaft was used to constantly stir the water sample at a speed of 150 r/min. Carbon steel coupons (20#) were suspended on a rack using iron wire, with the height adjusted to ensure the coupons were fully immersed in the water sample. Corrosion tests were conducted at 25 and 40 °C constant temperature water baths for 72 h. Before and after the test, the 20# carbon steel coupons were weighed using a precision electronic balance to calculate the annual corrosion rate and corrosion inhibition rate. The formulas for calculating the annual corrosion rate X (mm/a) and corrosion inhibition rate η (%) are as follows [18]:

$$X = \frac{87600(m_0 - m)}{\text{spt}} \quad (3)$$

$$\eta = \frac{X_0 - X_1}{X_0} \times 100\% \quad (4)$$

where m is the mass of the corroded coupon after the experiment (g), m_0 is mass of the corroded coupon before the experiment (g), s is the surface area of the corroded coupon (28.7 cm^2), ρ is the density of the corroded coupon (7.86 g/cm^3), t is the experiment duration (72 h), X_0 is the annual corrosion rate of the blank control group without additive (mm/a), and X is the annual corrosion rate of the test group with different additive dosages (mm/a).

3. Results

3.1. Water Quality Analysis

Conductivity can indirectly reflect the concentration of dissolved ions in the cooling water. Higher cooling water conductivity indicates a higher concentration of dissolved ions, which will significantly increase the tendency of scaling and corrosion [19]. Generally, the conductivity of cooling water should be between 100–1500 $\mu\text{S/cm}$. The conductivity test results shown in Figure 1a, with the minimum conductivity of 426 $\mu\text{S/cm}$ on 22 August 2021 and the maximum conductivity of 747 $\mu\text{S/cm}$ on 2 March 2022, indicate that the conductivity of all samples met the requirements and did not experience significant fluctuations. With the increase in months, the conductivity of each sample generally showed an upward trend, which may be due to the increase in temperature. When the cooling water turbidity is relatively high, the tendency of scaling and corrosion in the cooling system will also increase significantly. Generally, the turbidity of cooling water should be less than 10 NTU. The turbidity test results shown in Figure 1b, with the minimum turbidity of 0.62 NTU on 22 August 2021 and the maximum turbidity of 4.62 NTU on 18 August 2022, indicate that the turbidity of all samples met the requirements. The pH of cooling water has a significant impact on the corrosion and scaling of the cooling water system [20]. When the pH of the cooling water is higher, it promotes the dissociation of HCO_3^- into H^+ and CO_3^{2-} , increasing the concentration of CO_3^{2-} and facilitating scaling; when the pH of the cooling water is lower, it is not conducive to scaling, but due to its acidity, it is favorable for corrosion. Generally, the pH of cooling water should be 6.8–9.5. The pH test results of the water quality samples at different periods shown in Figure 1c indicate that, except for the samples on 22 August 2021, 31 March 2022, and 24 May 2022 which had a pH below 8.0, the remaining samples were all within the range of 8.0–9.0 and relatively stable.

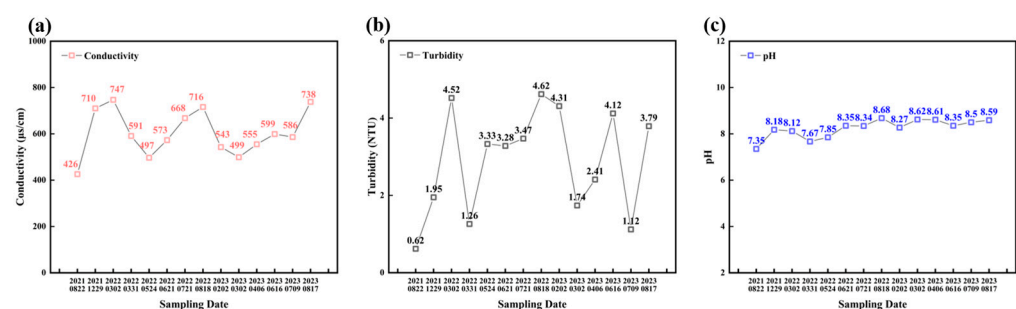


Figure 1. Cooling water samples at different time intervals: (a) conductivity; (b) turbidity; (c) pH value.

Water hardness refers to the total concentration of all metal ions except alkali metals. In cooling water, the hardness is mainly composed of calcium and magnesium, so the cooling water hardness usually refers to the sum of calcium hardness and magnesium hardness. Groundwater often contains relatively high concentrations of Ca^{2+} and Mg^{2+} , and these two ions are the main scale-forming cations in the cooling water during the circulation process. Therefore, their concentrations cannot be too high, otherwise, a large amount of scale will form throughout the cooling water system, seriously affecting the heat transfer efficiency. The Ca^{2+} and Mg^{2+} concentrations of the water quality samples at different periods are shown in Figure 2. The maximum Ca^{2+} concentration was

3.07 mmol/L in the sample taken on 17 August 2023, and the minimum was 1.71 mmol/L in the 22 August 2021 sample. Overall, it showed an increasing trend over time, mainly due to the concentration of the cooling water as the number of circulation cycles increased. In the cooling water, the Ca^{2+} concentration should not exceed 5 mmol/L and should not be less than 0.75 mmol/L, so all the water quality samples met the requirements. The maximum Mg^{2+} concentration was 0.69 mmol/L in the sample taken on 15 June 2023, and the minimum was 0.12 mmol/L in the 24 May 2022 sample, without any obvious trend observed. In the circulating cooling water, the Mg^{2+} concentration should not exceed 2.5 mmol/L, and all the water quality samples met this requirement.

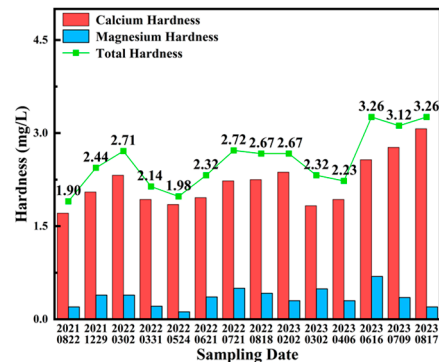


Figure 2. Cooling water samples at different time intervals: total hardness, calcium hardness, and magnesium hardness.

Alkalinity is a parameter that indicates the water's ability to absorb protons, usually measured by the total amount of substances in the water that can react with a strong acid. It is an important indicator for evaluating the water quality of cooling water. In circulating cooling water, the main components of alkalinity are bicarbonate, carbonate, and hydroxide, among which bicarbonate is the primary form. When using water with a relatively high bicarbonate content as cooling water, there is a tendency to form CaCO_3 precipitates [21]. The HCO_3^- concentrations of the water quality samples at different periods are shown in Figure 3. The maximum value was 3.32 mmol/L in the sample taken on 17 August 2023, and the minimum was 0.71 mmol/L in the sample taken on 31 March 2022. Overall, the HCO_3^- concentration in the external cooling water system of this synchronous condenser shows an increasing trend over time, which may be due to the higher HCO_3^- concentration in the make-up water and the concentration of the cooling water after multiple cycles.

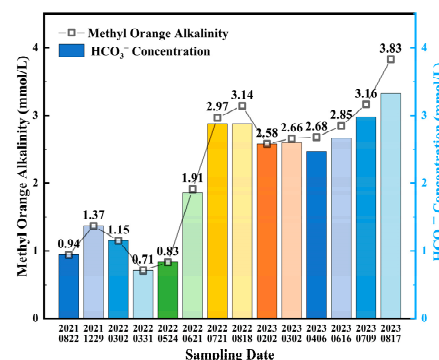


Figure 3. Cooling water samples at different time intervals: alkalinity and HCO_3^- concentration.

Generally, chlorine or sodium hypochlorite is added to control the growth of microorganisms in the circulating cooling water. However, Cl^- is a corrosive ion that can destroy the passivation film on the surface of carbon steel, stainless steel, and aluminum metals and alloys, causing pitting corrosion, crevice corrosion, and stress corrosion cracking [22]. Therefore, the Cl^- concentration in the circulating cooling water must be controlled. The

Cl^- concentrations of the water quality samples at different periods are shown in Figure 4a. The maximum Cl^- concentration was 2.02 mmol/L in the sample taken on 17 August 2023, and the minimum was 0.87 mmol/L in the sample taken on 24 May 2022. SO_4^{2-} is also a corrosive ion and may form calcium sulfate scale with the Ca^{2+} in the cooling water, so it also needs to be monitored [23]. The SO_4^{2-} concentrations of the water quality samples at different periods are shown in Figure 4b. The maximum SO_4^{2-} concentration was 1.73 mmol/L in the sample taken on 2 March 2022, and the minimum was 0.58 mmol/L in the sample taken on 2 March 2023. In this external cooling water system of the synchronous condenser, the concentrations of these two ions are relatively low.

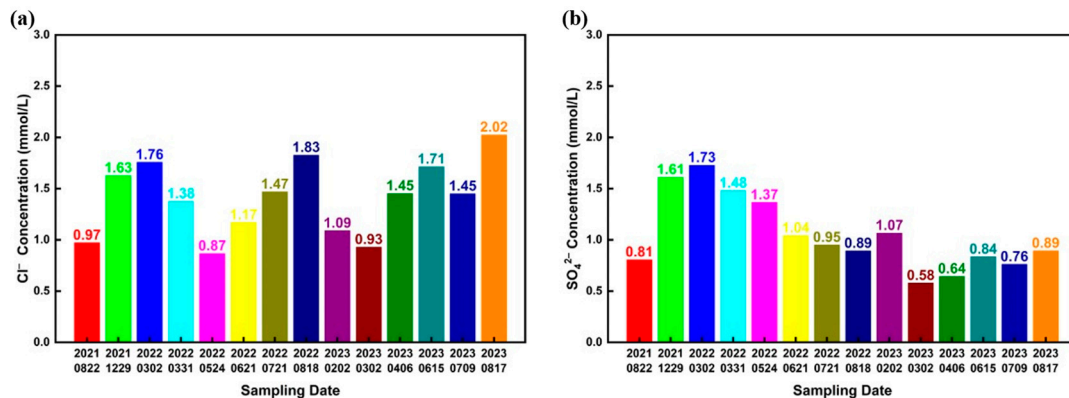


Figure 4. Cooling water samples at different time intervals: (a) Cl^- concentration; (b) SO_4^{2-} concentration.

Through the analysis of the test data of the cooling water samples collected from the external cooling water system of a 300 Mvar dual internal water cooling synchronous condenser at different periods, the results show that the water quality control of the external cooling water has been well maintained in the past three years. The conductivity, pH value, turbidity, alkalinity, hardness, and concentrations of various anions and cations are all controlled within a relatively reasonable range. However, it can also be observed that with the prolonged operation time, the cooling water has undergone concentration during the multiple circulation processes, and the various dissolved or suspended substances have basically experienced a certain degree of enrichment, showing a periodic change pattern. In the long run, this will significantly aggravate the scaling, corrosion, and microbial growth problems in the circulating cooling water system, thereby affecting the system's heat transfer efficiency and compromising the safe and reliable operation of the system. Therefore, further research is needed to improve the operation control methods of this synchronous condenser's external cooling water system.

3.2. Performance Evaluation and Optimal Dosage of Corrosion and Scale Inhibitors

The static scale inhibition tests and rotating coupon corrosion tests directly used the water samples taken from the external cooling water system of the converter station's synchronous condenser as the test water. The basic properties of the test water are shown in Table 1.

Table 1. Water for test.

Parameter	pH	Conductivity ($\mu\text{S}/\text{cm}$)	Alkalinity (mg/L)	Calcium Hardness (mg/L)	Total Hardness (mg/L)
External cooling water	8.10	600	45	225	262.5

The main factor affecting the corrosion and scaling of the external cooling water system is the water quality of the external cooling water. Predicting the corrosion and

scaling trends of this cooling water is crucial to studying the optimal dosage under these water quality conditions. Combining the Langelier Saturation Index (LSI), Ryznar Stability Index (RSI), and Puckorius Scaling Index (PSI), the corrosion and scaling trends of the test water were predicted. An LSI of less than 0 tends towards corrosion, and greater than 0 tends towards scaling; an RSI of less than 3.7 tends towards severe scaling, in the range of 3.7–6.0 tends towards scaling, in the range of 6.0–7.5 tends towards corrosion, and greater than 7.5 tends towards severe corrosion; a PSI of less than 6 tends towards scaling, and greater than 6 tends towards corrosion [24]. The three indices were calculated for the external cooling water samples of the converter station at 25 and 40 °C to analyze their corrosion and scaling tendencies, and the results are shown in Table 2.

Table 2. Analysis of corrosion and scaling in different temperatures.

Temperature (°C)	LSI	LSI Analysis	RSI	RSI Analysis	PSI	PSI Analysis
25	−0.18	Prone to corrosion	8.46	Severe corrosion	9.60	Prone to corrosion
40	0.09	Prone to scaling	7.92	Severe corrosion	9.06	Prone to corrosion

From the index values in Table 2, it can be judged that the external cooling water samples of the converter station are mainly characterized by corrosion at both temperatures. Particularly, the RSI index is 8.46, indicating a tendency towards severe corrosion. Once the corrosion problem occurs, it is an irreversible process, so it is necessary to focus on the corrosion inhibition performance of the scale inhibitor at different temperatures, and then determine the optimal dosing scheme to avoid serious corrosion damage caused by inaccurate dosing schemes.

First, a calcium carbonate deposition experiment was conducted to test the scale inhibition effect when different amounts of the commercial corrosion and scale inhibitor AS-582 were added to the water samples from the external cooling water system of the converter station's synchronous condenser. The scale inhibition rate results are shown in Figure 5.

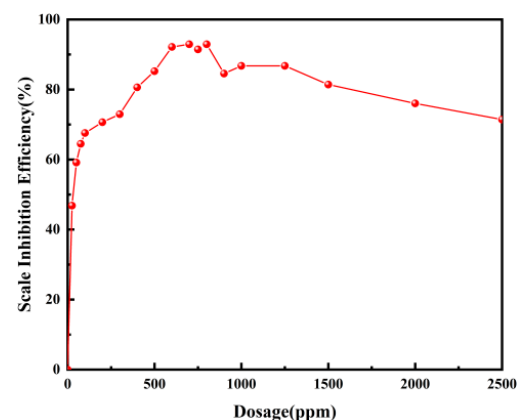


Figure 5. The effect of scale inhibition on CaCO_3 precipitation at various mass concentrations of scaling inhibitor dosage.

As shown in Figure 5, the scale inhibition rate first increases and then decreases with the increase in the corrosion and scale inhibitor dosage. When the dosage is increased from 0 to 100 ppm, the scale inhibition rate rapidly increases to 67.58%. The mechanism of action of scale inhibitors is that some functional groups in their molecules can be electrostatically adsorbed onto the surface of crystal nuclei formed by scaling metal salts, inhibiting crystal growth or causing crystal distortion, thereby achieving the purpose of scale inhibition.

Therefore, adding a small amount of corrosion and scale inhibitors can stabilize calcium ions with much higher stoichiometry in water [25]. Then, as the dosage increases to 600 ppm, the scale inhibition rate gradually increases to 92.15%. When the dosage is in the range of 600–800 ppm, the scale inhibition rate varies little, fluctuating around 92%. After exceeding 800 ppm, the scale inhibition rate gradually decreases with the increase in the corrosion and scale inhibitor concentration, showing a relatively obvious “threshold effect” [26]. Therefore, for this converter station’s external cooling water system, the optimal dosage of the commercial corrosion and scale inhibitor AS-582 with the best scale inhibition effect is 600 ppm.

Furthermore, we conducted carbon steel corrosion experiments at 25 and 40 °C, respectively, to test the corrosion inhibition effect when different amounts of the commercial corrosion and scale inhibitor AS-582 were added to the external cooling water samples of the converter station’s synchronous condenser. The results of the annual corrosion rate and corrosion inhibition rate are shown in Figure 6.

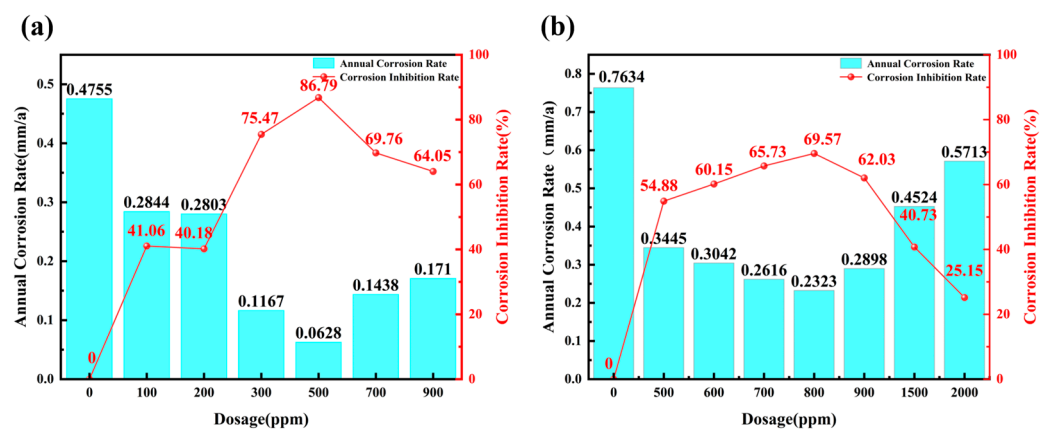


Figure 6. Variation of annual corrosion rate and inhibition efficiency with dosage at (a) 25 °C; (b) 40 °C.

Figure 6a shows the test results at 25 °C. Without any dosing, the maximum annual corrosion rate was 0.4755 mm/a. As the dosage increases, the annual corrosion rate first decreases and then increases, with the optimal dosage being 500 ppm. At a dosage of 500 ppm, the corrosion inhibition rate reached the highest at 86.79%, and the annual corrosion rate was the lowest at 0.0628 mm/a.

Figure 6b shows the test results at 40 °C. At each dosage, the carbon steel corrosion rate at 40 °C was significantly higher than that at 25 °C. Without any dosing, the annual corrosion rate was the highest at 0.7634 mm/a, and severe corrosion could be observed during the experiment. As the dosage increases, the annual corrosion rate shows a similar trend of first decreasing and then increasing, with the optimal dosage being 800 ppm. At a dosage of 800 ppm, the corrosion inhibition rate and annual corrosion rate were 69.57% and 0.2323 mm/a, respectively, which cannot meet the requirements, indicating a poor corrosion inhibition effect.

Combining the carbon steel corrosion tests at the two different temperatures, the following conclusions can be drawn:

- (1) When the dosage exceeds the optimal dosage, the corrosion inhibition rate gradually decreases, showing a clear “threshold effect”. This proves that the dosage should not be arbitrarily increased, as excessive dosing not only increases the dosing cost and environmental pressure but also leads to a decrease in the corrosion inhibition effect, posing a potential risk to the stable operation of the external cooling water system.
- (2) As the test temperature increases from 25 to 40 °C, the annual corrosion rate increases significantly, and the commercial corrosion and scale inhibitor AS-582 not only has a change in the optimal dosage but also a significant decrease in the corrosion inhibition effect, requiring the use of additional corrosion inhibitors.

4. Conclusions

This paper first conducted detection and analysis of the water quality of a 300 Mvar dual internal water cooling synchronous condenser's external cooling water system. Over the past three years, the water quality has been good, with the conductivity, pH value, turbidity, alkalinity, hardness, and concentrations of various anions and cations all controlled within a relatively reasonable range. However, the cooling water has undergone concentration during the multiple circulation processes, and in the long run, the scaling and corrosion problems in the external cooling water system will become more severe, thereby affecting the safe and stable operation of the system. Therefore, it is necessary to further improve the dosing scheme for this synchronous condenser's external cooling water system.

Through the LSI, RSI, and PSI, the water samples from this synchronous condenser's external cooling water system were evaluated, and the results showed that the water quality of this external cooling water system tends towards corrosion, requiring more attention to be paid to anti-corrosion during routine operation and maintenance. The static scale inhibition tests showed that the optimal dosage of the commercial corrosion and scale inhibitor AS-582 with the best scale inhibition effect is 600 ppm, with a scale inhibition rate of 92.15%. The rotating coupon corrosion tests showed that at 25 °C, the optimal dosage for corrosion inhibition is 500 ppm, with a corrosion inhibition rate of 86.79% and an annual corrosion rate of 0.0628 mm/a, achieving an ideal corrosion inhibition effect. At 40 °C, the dosage with the best corrosion inhibition effect is 800 ppm, with a corrosion inhibition rate and annual corrosion rate of 69.57% and 0.2323 mm/a, respectively, indicating a poor corrosion inhibition effect, requiring the use of additional corrosion inhibitors in combination.

Due to the existence of the "threshold effect", it is very meaningful to explore the optimal dosage of the corrosion and scale inhibitor at different temperatures, as this can not only achieve the best corrosion inhibition effect but also effectively reduce the dosing cost and environmental pressure.

Author Contributions: Validation, Y.X.; formal analysis, X.G. (Xiantao Gu); investigation, X.G. (Xingwang Guo), X.C., Y.G., Z.L. and X.G. (Xiantao Gu); resources, X.M.; data curation, J.Z., P.F. and H.D.; writing—original draft preparation, X.G. (Xiantao Gu); writing—review and editing, L.Y.; visualization, Y.W. (Yuquan Wu), Q.J. and Y.W. (Yan Wu); project administration, Z.Z.; funding acquisition, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [Key technical research on the "smart" control system of external cooling water for phase-shifting cameras used in the 2023 ultra-high voltage converter station of State Grid Anhui Electric Power Research Institute] grant number [2023GFW-0737].

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

Conflicts of Interest: Authors Junjie Zhang, Peipei Fan, Haosheng Dong, Xiaowei Ma, Zhikui Liu and Xingwang Guo were employed by the company State Grid Anhui Extra High Voltage Company. Authors Zhongkang Zhou, Qiaozhen Ji and Yan Wu were employed by the company Anhui Xinli Electric Power Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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