Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29362

289 (2023) 62–72
March

Circulating cooling water treatment of thermal power plant based on microbial treatment process

Ning Liu[a,b], Xingyu Liu[a,c,d,*], Liangshi Wang[a,e], Xuezhe Zhu[a,e], Qiyuan Gu[a,e]

[a]*National Engineering Research Center for Environment-Friendly Metallurgy in Producing Premium Non-Ferrous Metals, GRINM Group Co., Ltd., Beijing 101407, China, emails: wellwoodliu@163.com (X. Liu), 31605016@qq.com (N. Liu), wangliangshi@grinm.com (L. Wang), zhuxuezhe2020@163.com (X. Zhu), guqiyuan@grinm.com (Q. Gu)*
[b]*Key Laboratory for Ecological Metallurgy of Multi-Metallic Mineral (Ministry of Education), School of Metallurgy, Northeastern University, Shenyang 110819, China*
[c]*Institute of Earth Science, China University of Geosciences, Beijing 100083, China*
[d]*Shenzhen Green-Tech Institute of Applied Environmental Technology Co., Ltd., Shenzhen 518001, China*
[e]*GRINM Resources and Environment Tech. Co., Ltd., Beijing 101407, China*

Received 23 August 2022; Accepted 21 January 2023

ABSTRACT

Circulating cooling water consumes a large amount of water in thermal power plant, and there are some problems such as scaling and corrosion in the system. This study presents a novel circulating cooling water treatment process based on microbes. The mechanism and influencing factors of microbial treatment process of circulating cooling water is studied. Water from circulating cooling system of a 300 MW thermal power unit was used, dynamic simulation test was carried out and compared between the microbial treatment process and the traditional chemical treatment process. The results showed that nutrient solution dosage on calcium hardness is positive, while the interaction between nutrient solution dosage and aeration rate has negative effect. When ammonia concentration is 10–50 mg/L and aeration rate is 1–3 L, and the minimum calcium hardness is 18.3 mmol/L. Reducing the concentration of nutrient solution and increasing the aeration rate are beneficial to slow down the corrosion of carbon steel and stainless steel. When ammonia concentration is 10–50 mg/L and aeration rate is 1–3 L, the minimum corrosion rates are 0.01552 and 0.00110 mm/a, respectively. Compared with traditional chemical treatment process, the microbial treatment process can achieve the scale inhibition and corrosion inhibition target at high concentration ratio, the highest concentration ratio can reach 5.4, and the corrosion rate of carbon steel and stainless steel is low. The green, efficient and environment-friendly microbial treatment process provides a new method for circulating cooling water treatment, which can obtain stable and economical operation of circulating cooling water system under high concentration ratio.

Keywords: Circulating cooling water; Microbial method; Corrosion and scale inhibition; Dynamic simulation test; All-factor design

1. Introduction

Thermal power plants are major industrial water users, accounting for 60% of industrial water consumption, while the water consumption of circulating cooling water systems in power plants accounts for about 70% of the total water consumption for operation. Therefore, reducing water consumption in circulating cooling water system in power plants is of great significance to save industrial water usage [1–3]. Increasing the concentration ratio of circulating cooling water is an effective way to improve the reuse rate of water. However, high concentration ratio can lead to

---

* Corresponding author.

corrosion, scaling and microbial growth in equipment and pipelines due to water quality deterioration [4–6]. Therefore, improving the treatment process of circulating cooling water is the key to minimize these problems.

Traditional circulating cooling water treatment technologies include physical method, chemical method, physical-chemical method, etc. [3,7], and chemical treatment is commonly used. By adding chemicals into the circulating water system, the corrosion, scaling and slime production can be effectively inhibited. For example, Brânzoi et al. [8] added organic polymer synthesized by free radical polymerization in circulating cooling water to inhibit corrosion and scaling; He et al. [9] developed a combination agent of polyaspartic acid, polyepoxysuccinic acid, polyamino polyether methylene phosphate and sodium gluconate, and the results showed that this agent can inhibit the corrosion of carbon steel in highly corrosive soft water; Wang et al. [10] studied the effect of water extract of tobacco on circulating cooling water system, and found that it played corresponding roles of corrosion inhibition, scale inhibition and biocidal activity in different aspects. However, many studies also indicated that adding chemicals is costly, difficult to manage, and easy to cause secondary pollution, which may cause new equipment corrosion [9,11].

Compared with traditional treatment methods, microbial method has the advantages of high efficiency, low cost and environmental friendliness, which is promising for circulating cooling water treatment [12]. For example, Chen et al. [13] developed a compound microbial inhibitor for circulating cooling water to control scaling, corrosion and biofouling of water system. The results showed that this microbial inhibitor can obviously improve the water quality, and the corrosion inhibition rate and biofouling removal rate were 99.69% and 22.21%, respectively; Beni and Esmaeili [14] proposed a method for removing heavy metals from industrial wastewater based on biosorption, and systematically studied the effects of pH, temperature, dosage of biosorbent, retention time and functional groups on removal efficiency to obtain the optimum conditions of biosorption reaction.

In this study, the microbial treatment process for circulating cooling water treatment was studied in a 300 MW thermal power unit in China and the effects of nutrient solution dosage, bacteria liquid dosage and aeration rate on scale inhibition and corrosion inhibition were evaluated by full-factor test method. The dynamic simulation test further verified the advantages of microbial method compared with the traditional chemical method in the treatment of circulating cooling water.

2. Theory and experimental method

2.1. Theory

During the operation of the circulating cooling water system, the water quality will inevitably change due to the circulating water concentration, which will bring hazards such as scaling, corrosion and bacteria and algae breeding. Circulating cooling water treatment is to solve these problems, so as to achieve stable production, save water resources, save costs and improve economic benefits [3,4,15].

Biological enhancement is a technology that periodically add microbes to the circulating cooling water, and uses biological enzymes and microbial degradation to solve the problems of scaling, corrosion and microbial growth in the circulating cooling water system [13]. This technology has great advantages in improving the concentration ratio of circulating cooling water, saving water and energy, and protecting the environment.

The main mechanisms of biological corrosion and scale inhibition technology are shown in Fig. 1 [3]. The biological enzymes produced by microorganisms are used to complexly solubilize and flocculate the scaling metal ions in circulating cooling water, thereby inhibiting the scaling. The dominant flora of oxygen-consuming microorganisms is formed in the circulating cooling water system, so the dissolved oxygen in the cooling water is reduced and the reproduction of aerobic corrosive microorganisms is inhibited, based on this the corrosive niche is seized and the occurrence of microbial corrosion is reduced to achieve the corrosion inhibition effect. Reducing or avoiding the use of phosphorus-containing agents, cutting off the supply of phosphorus, a nutrient necessary for the growth of bacteria and algae in cooling water, and inhibiting their growth, reducing the breeding of microorganisms and the formation of biological slime.

2.2. Experimental method

The microbial treatment ecosystem of the circulating cooling water was constructed by adding corresponding compound microbial agent (including compound microbial flora and microbial nutrition regulator made by fermentation process) into the circulating cooling water. The treatment effect of microbial method on circulating cooling water was verified through the test and analysis of scale inhibition and corrosion inhibition performance, and the main influencing factors were analyzed. The experiments were carried out in triplicate.

Scale inhibition performance test: the scale inhibition performance was tested based on static scale inhibition method. Briefly, 5 L of circulating cooling water for

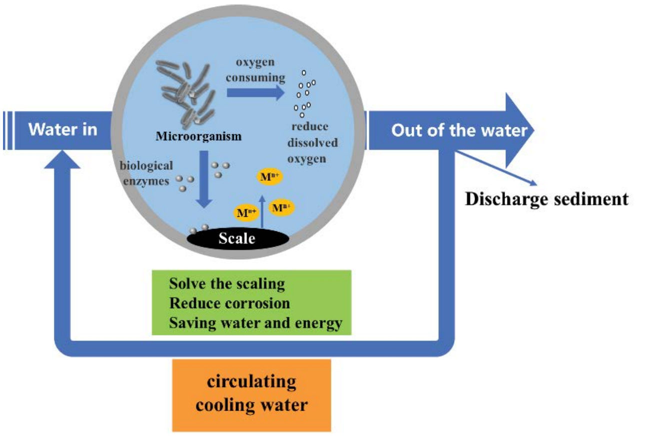

Fig. 1. Mechanisms of biological corrosion and scale inhibition technology.

experiment was added into a beaker, and then a certain volume of compound microbial preparation is added. The beaker was placed in a constant-temperature water bath and heated at 50°C ± 5°C and stirred with a rotating speed of 150 rpm for evaporation and concentration. During the test, continuous water supply was controlled to supplement evaporation and sampling loss. Calcium hardness, hardness, alkalinity, conductivity, chloride and pH value of the water were measured regularly, and the end point of the test was set according to the ultimate carbonate hardness test method. The experiments were carried out in triplicate.

Corrosion inhibition performance test: the corrosion inhibition performance was tested using the coupon weight loss method. RCC-I coupon weight loss corrosion tester was used to regularly record the color changes of sample pieces during the test. After the test, the hanging pieces were taken out and weighed, and the corrosion rate was calculated. Three hanging pieces are suspended in each group, and the experiments were carried out in triplicate.

3. Results and discussions

3.1. Scaling inhibition effect

This section mainly discusses the study of microbial method on the scale inhibition effect of circulating cooling water by. The influences of nutrient solution dosage, microbial inoculum dosage and aeration rate on the scale inhibition effect were investigated through full-factor experiment to obtain the optimum scale inhibition process conditions [16,17].

3.1.1. Study on scale inhibition effect

The water used in this test was taken from the circulating cooling water of a 300 MW plant in China, which possesses high hardness and alkalinity. Two groups of water samples were treated by microbial treatment and traditional chemical treatment, respectively [18]. The water quality was tested and analyzed based on the methods mentioned-above, and the test results are shown in Tables 1 and 2.

The results show that compared with traditional chemical method, the limit value that the microbial method can process is higher than that of traditional chemical method, and the scale inhibition effect of microbial treatment is better under the same conditions.

3.1.2. Scale inhibition mechanism analysis

During the experiment, three factors were selected to evaluate, including the amount of nutrient solution, bacteria liquid and aeration rate. For each factor, two levels were studied and the ultimate calcium carbonate hardness value was evaluated as response. A full-factor experimental design was conducted to study the influence of each factor on the scale inhibition effect [19,20]. The experimental factor level table is shown in Table 3, and the full-factor experimental design table and experimental results are shown in Table 4 (experiments were repeated twice at the center).

According to the results of all-factor test, the analysis of variance was performed (Table 5). The results show that the *P*-value of the fitted model in this experiment was less than 0.001, which indicates that the fitting degree of the equation was adequate. The bending term *P* was 0.198 (higher than 0.05), indicating that the bending was not significant. Therefore, the model was considered as linear. Among the factors evaluated, the *P*-value of nutrient solution dosage was 0 (less than 0.05), while the *P*-values of strain dosage and aeration rate were both 0.641, which indicates that the effect of nutrient solution dosage on calcium hardness was significant, but that of strain dosage and aeration rate was not significant.

From the results of variance analysis of two-factor interaction, the *P*-value corresponding to the combination of nutrient solution dosage and aeration rate was 0.036,

Table 1
Water quality analysis and static test results of test water

Water sample name	First batch of raw water	Second batch of raw water	Third batch of raw water
Cl^- (mg/L)	67.7	68.5	67.0
PA (mmol/L)	0	0	0
MA (mmol/L)	6.0	6.1	6.0
YD (mmol/L)	8.0	8.1	8.05
Ca^{2+} (mmol/L)	4.60	4.62	4.60
pH	7.67	7.66	7.66
DD (μS/cm, 25°C)	1,030	1,031	1,025

PA refers to phenolphthalein alkalinity;
MA refers to methyl orange alkalinity (total alkalinity);
DD refers to total dissolved solids;
YD refers to hardness.

Table 2
Comparison of static comprehensive scale inhibition performance

Number	Scheme	Hardness (mmol/L)		Alkalinity (mmol/L)		Calcium hardness (mmol/L)	
		Maximum	Threshold	Maximum	Threshold	Maximum	Threshold
1	Raw water (7 mg/L chemicals) + 8 mg/L scale inhibitors + 2 mL (1 mmol/mL) sulfuric acid	31.6	30.2	8.95	8.40	18.90	18.12
2	Raw water (7 mg/L chemicals) + 2 mL (1 mol/mL) sulfuric acid	21.99	21.34	5.78	5.40	13.10	12.85
3	Raw water (7 mg/L chemicals) + 0.5‰ inoculation amount + 0.07‰ nutrient solution	35.70	35.30	–	–	21.95	21.5

Table 3
Scale inhibition test factor level of circulating cooling water

Factors	*A*: Amount of nutrient solution (‰)	*B*: Amount of bacteria liquid (‰)	*C*: Amount of aeration (L/min)
High	0.07	0.5	3
Low	0.03	0.1	1

Table 4
Scale inhibition test table of circulating cooling water (experiments were repeated twice at the center)

Numbers	*A*	*B*	*C*	Calcium hardness limits (mmol/L)
1	–1	1	1	18.5
2	–1	–1	1	18.3
3	0	0	0	19.8
4	–1	1	–1	18.8
5	1	1	–1	21.2
6	–1	–1	–1	18.8
7	0	0	0	19.8
8	1	–1	1	21.5
9	1	1	1	21.4
10	1	–1	–1	21.1

Table 5
Variance analysis of scale inhibition experiment of circulating cooling water

Item	Freedom	Adj. SS	Adj. MS	*F*-value	*P*-value
Model	6	14.84	2.4733	132.5	0.001
Linearity	3	14.59	4.8633	260.54	0
A	1	14.58	14.58	781.07	0
B	1	0.005	0.005	0.27	0.641
C	1	0.005	0.005	0.27	0.641
Two-factor interaction	3	0.25	0.0833	4.46	0.125
AB	1	0.005	0.005	0.27	0.641
AC	1	0.245	0.245	13.13	0.036
BC	1	0	0	0	1
Error	3	0.056	0.0187		
Bending	1	0.036	0.036	3.6	0.198
Mismatching	1	0.02	0.02	*	*
Pure error	1	0	0		
Sum	9	14.896			

less than 0.05, which indicates that the interaction effect of nutrient solution dosage and aeration rate had an important influence on calcium hardness. On the contrary, the interaction effect of the combination of nutrient solution and strain dosage, and the combination of strain dosage and aeration rate had no significant effect on calcium hardness. Therefore, the three factors can affect the scale inhibition effect through different functions, which indicates that the microbial method can effectively inhibit scaling.

Table 6 lists the effect-coefficient of nutrient solution dosage, strain dosage, aeration rate and interaction effects among the three factors. When the value of T is positive, it indicates that the influence of this influencing factor on calcium hardness is a positive effect, and appropriately increasing the level of this factor is beneficial to improve the response value; a negative value of T indicates opposite trend. Based on the above analysis of variance results, the effects of nutrient solution dosage and the combination of nutrient solution dosage and aeration rate on calcium hardness were significant. It can be seen from Table 6 that the effect of nutrient solution dosage on calcium hardness was positive, while the interaction of nutrient solution dosage and aeration rate had a negative effect on calcium hardness.

Fig. 2 shows the Pareto diagram of three different influencing factors and the standardized effects among them, which confirms the conclusion drawn from the variance analysis (Table 4). Among the evaluated factors, the nutrient solution dosage had the most significant effect on the ultimate calcium hardness, followed by the combination of nutrient solution dosage and aeration rate. The standard effect values of other influencing factors were all lower than 3.18, which is considered as insignificant.

In order to further verify the influence of all-factor experimental design results, the residual plots analysis of scale inhibition experiment was used, and the results are shown in Fig. 3. It can be seen from Fig. 3a that the residual plots are distributed around 0, which indicates that the adopted regression model was suitable for the original data. The standard residual normal probability diagram (Fig. 3b) indicates the data follows a normal distribution.

In order to further study and obtain the optimal process conditions of microbial method for the treatment of circulating cooling water, the following optimization processes were conducted. Since the above statistical analysis results showed that only the effect of nutrient solution dosage, aeration amount, and the combination of nutrient solution dosage and aeration rate were significant. Therefore, these three factors were selected to re-fit the model, and the obtained results of analysis of variance are shown in Table 7. The results showed that the *P*-values of nutrient solution dosage, the combination of nutrient solution dosage and aeration rate were 0 and 0.003, respectively, which were all less than 0.05, indicating the effect on the value of calcium hardness was still significant. The *P*-value of bending term was 0.058, which indicates that there is bending phenomenon in this model. It can be seen from the effect coefficient table (Table 8) that the effect of the combination of nutrient solution dosage and aeration rate on the response changed from negative to positive after the model was re-fitted.

As shown in the residual experimental diagram (Fig. 4), the points in the diagram basically fell on a straight line, indicating that the optimized model had an adequate goodness of fit and the stability between independent variables was high. The fitted model after optimization could better reflect the effects of various factors on the limit calcium hardness than the equation before optimization.

The regression analysis of the fitting model before and after the optimization was listed in Table 9. It can be seen from the table that the *S* value of ultimate calcium hardness after optimization is lower than that before optimization, and the *R*-sq. (adjusted) value increased from 98.87% to 99.34% after optimization, indicating that the model after optimization is significantly superior to the model before. The obtained regression equation is:

$$Y = 18.470 + 0.05A = 0.2875C + 0.00875AC \tag{1}$$

where *Y* is the calcium hardness, *A* is the nutrient solution dosage and *C* is the aeration amount.

The *P*-value in the residual normality test was 0.655, indicating that the residual distribution conformed to the normal distribution. At the same time, the contour map of

Table 6
Effect-coefficient table of scale inhibition experiment of circulating cooling water

Item	Effect	Coefficient	Coefficient standard error	*T*	*P*	Variance expansion factor
Constants	19.92	0.0432	461.06	0		
A	2.7	1.35	0.0483	27.95	0	1
B	0.05	0.025	0.0483	0.52	0.641	1
C	–0.05	–0.025	0.0483	–0.52	0.641	1
AB	–0.05	–0.025	0.0483	–0.52	0.641	1
AC	0.35	0.175	0.0483	3.62	0.036	1
BC	0	0	0.0483	0	1	1

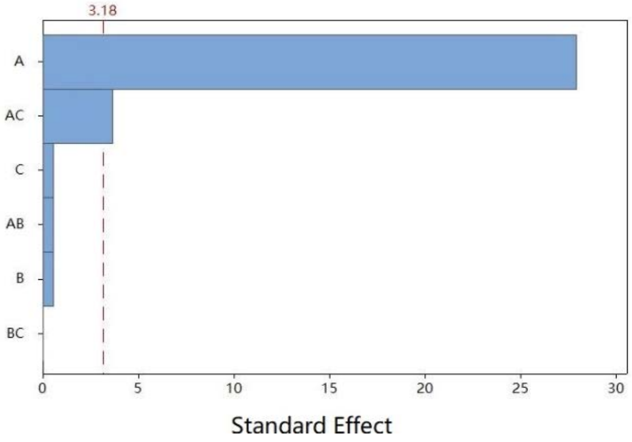

Fig. 2. Pareto diagram of standardization effect of scale inhibition experiment.

Table 7
Analysis of variance of scale inhibition experiment after optimization

Item	Freedom	Adj. SS	Adj. MS	*F*	*P*
Model	3	14.83	4.9433	449.39	0
Linearity	2	14.585	7.2925	662.95	0
A	1	14.58	14.58	1,325.45	0
C	1	0.005	0.005	0.45	0.525
Two-factor interaction	1	0.245	0.245	22.27	0.003
AC	1	0.245	0.245	22.27	0.003
Error	6	0.066	0.011		
Bending	1	0.036	0.036	6	0.058
Mismatching	4	0.03	0.0075	*	*
Pure error	1	0	0		
Sum	9	14.896			

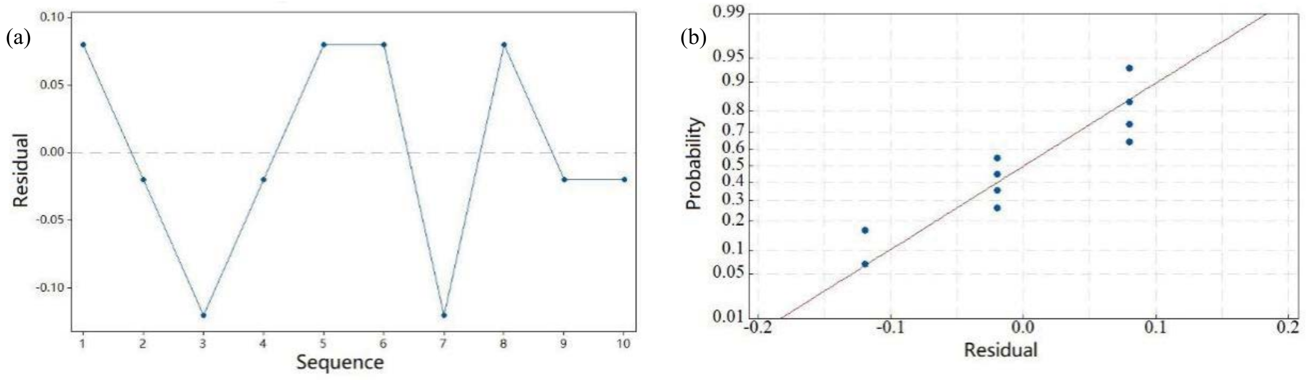

Fig. 3. Residual plot of scale inhibition experiment. (a) Residual-observation sequence and (b) residual.

Table 8
Scale inhibition experimental effect coefficient table after optimization

Item	Effect	Coefficient	Coefficient standard error	*T*	*P*	Variance expansion factor
Constants		19.92	0.0332	600.61	0	
A	2.7	1.35	0.0371	36.41	0	1
C	–0.05	–0.025	0.0371	–0.67	0.525	1
AC	0.35	0.175	0.0371	4.72	0.003	1

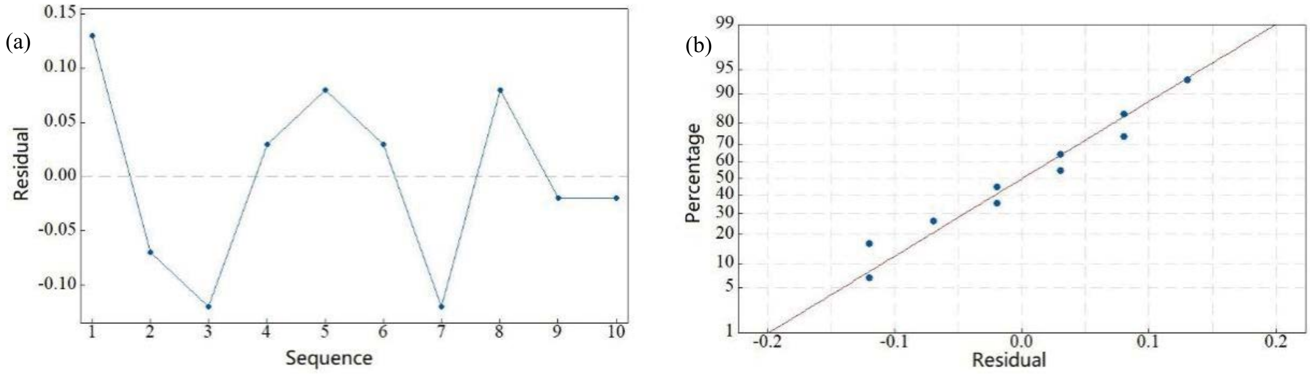

Fig. 4. Residual plot of scale inhibition experiment. (a) Residual-observation sequence and (b) residual distribution.

Table 9
Regression analysis table of scale inhibition experiment by optimization before and after deletion

	Before deletion	After deletion
S	0.136625	0.104881
R-sq.	99.62%	99.56%
R-sq. (Adjustment)	98.87%	99.34%
R-sq. (Prediction)	91.65%	98.86%

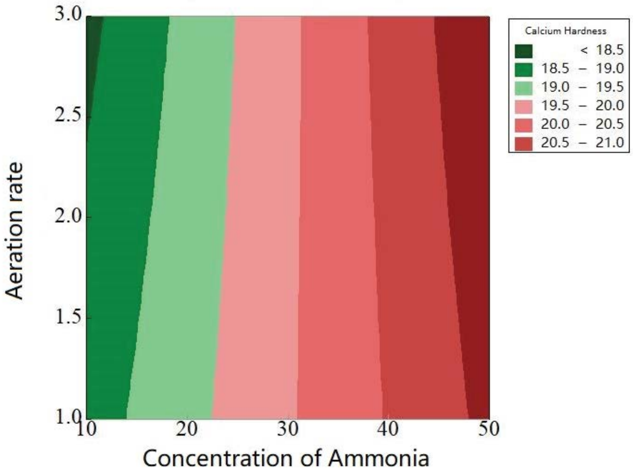

Fig. 5. Isoline diagram of nutrient solution consumption and aeration amount in scale inhibition experiment of high-alkali and high-calcium circulating cooling water after optimization.

nutrient solution consumption and aeration was obtained (Fig. 5) when the model was effective. It could be seen that with the increase of ammonia concentration, the calcium hardness also increased, while with the increase of aeration rate, the calcium hardness decreased. When the aeration rate was high, part of ammonia would overflow in gaseous state, which weakened the effective dose and accordingly reduced the calcium hardness.

In summary, the above results shows that the microbial method has a good inhibition effect on the scaling of circulating cooling water, and the dosage of nutrient solution or the combination of the dosage of nutrient solution and aeration rate had the greatest influence on calcium hardness. It was predicted that the calcium hardness would be the highest when the dosage of nutrient solution is 0.7‰, and the aeration rate is 1 L/min.

3.2. Corrosion inhibition effect

The carbon steel (20#) was selected to study the corrosion inhibition effect of the microbial method in the circulating cooling water, and the process conditions for obtaining the optimal corrosion inhibition effect were predicted through full-factor test.

Three factors including nutrient solution dosage, bacterial liquid dosage and aeration quantity were also selected to evaluate the corrosion inhibition effect, and two levels, high and low, were studied for each factor. The corrosion rate of carbon steel was evaluated as response, a full-factor test design was conducted to study the effect of each factor on the corrosion inhibition effect. The full-factor test design table and test results are shown in Table 10 (experiments were repeated twice at the center).

Table 10
Table for all-factor test of carbon steel corrosion (repeated at the center)

Number	*A*	*B*	*C*	Corrosion rate of carbon steel (mm/a)
1	–1	1	1	0.03327
2	–1	–1	1	0.03589
3	0	0	0	0.02890
4	–1	1	–1	0.03102
5	1	1	–1	0.01552
6	–1	–1	–1	0.03278
7	0	0	0	0.02983
8	1	–1	1	0.02665
9	1	1	1	0.02238
10	1	–1	–1	0.01760

Ten beakers with circulating cooling water were prepared and three pieces of carbon steel were placed in each beaker. The corrosion rate of carbon steel sheets before and after the test are listed in Table 11 and the comparative diagram of carbon steel sheets before and after corrosion (Fig. 6) were plotted. It can be seen that the corrosion rates of carbon steel sheets in the 10 beakers were basically between 0.015~0.035 mm/a, indicating that the influencing factors of microorganisms need to be further optimized to obtain the lowest corrosion rate.

According to the analysis of variance (Table 12), the *P*-value of the fitted model in this experiment was 0.007 (less than 0.05), which indicates that the selected linear model was fitted well; The *P*-value of the bending term is 0.032 (greater than 0.05), which further indicates that the bending was not significant and the model was linear. The *P*-value of missing term was 0.605, which was greater than 0.05,

Table 11
Test results of corrosion rate of rotating carbon steel sheet

Beaker number	Sheet number	Sheet weight before test W_0 (g)	Sheet weight after test W_1 (g)	Weight lost Δ1 (g)	Corrosion rate F_1 (mm/a)	Average F1 (mm/a)
	2197	21.3302	21.3220	0.0082	0.03556	
1	2198	21.3328	21.3255	0.0073	0.03178	0.03327
	2199	21.1874	21.1799	0.0075	0.03247	
	2191	22.4188	22.4107	0.0081	0.03486	
2	2192	22.5172	22.5088	0.0084	0.03618	0.03589
	2193	22.3761	22.3676	0.0085	0.03663	
	2194	22.3355	22.3290	0.0065	0.02826	
3	2195	22.3442	22.3373	0.0069	0.02980	0.02890
	2196	22.3107	22.3041	0.0066	0.02864	
	2090	22.5889	22.5815	0.0074	0.03180	
4	2091	22.6041	22.5973	0.0068	0.02943	0.03102
	2092	22.3603	22.3529	0.0074	0.03184	
	2093	22.5182	22.5142	0.0040	0.01715	
5	2094	22.4180	22.4144	0.0036	0.015727	0.01552
	2095	22.2901	22.2869	0.0032	0.013683	
	2096	22.4675	22.4593	0.0082	0.035497	
6	2097	22.1007	22.0931	0.0076	0.032949	0.03278
	2098	22.3922	22.3853	0.0069	0.02990	
	2099	22.3873	22.3804	0.0069	0.02988	
7	2110	22.4895	22.4827	0.0068	0.02923	0.02983
	2111	22.3042	22.2972	0.0070	0.03038	
	2112	22.3838	22.3778	0.0060	0.02585	
8	2113	21.8944	21.8882	0.0062	0.02687	0.02665
	2114	22.1804	22.1741	0.0063	0.02722	
	2115	22.0778	22.0726	0.0052	0.02272	
9	2116	22.1260	22.1207	0.0053	0.02294	0.02238
	2117	22.1808	22.1759	0.0049	0.02147	
	2118	22.2873	22.2830	0.0043	0.01875	
10	2119	22.0410	22.0376	0.0034	0.01475	0.01760
	2109	22.4822	22.4777	0.0045	0.01930	

Fig. 6. Changes of some carbon steel sheets before and after reaction.

indicating that there was no obvious difference between the predicted value and the experimental value, and the model selection is adequate. At the same time, among the three factors, the *P*-values of nutrient solution dosage and aeration rate were 0.002 and 0.028, respectively, both were less than 0.05, while the *P*-value of bacterial strain dosage was 0.135 (greater than 0.05), which indicates that nutrient solution dosage and aeration rate had significant effects on the corrosion rate of carbon steel, but bacterial strain dosage had no significant effects on the corrosion rate of carbon steel. From the results of variance analysis of two-factor interaction, the interaction effects of nutrient solution dosage and aeration rate, nutrient solution dosage and strain dosage, strain dosage and aeration rate on the corrosion rate of carbon steel were not significant.

On this basis, the interaction coefficients among nutrient solution dosage, strain dosage, aeration rate and the three factors were further studied (Table 13). A positive value of *T* indicates that the influence of this influencing factor on corrosion rate is positive; a negative value of *T* indicates opposite trend. Table 12 shows that the amount of nutrient solution and aeration rate had significant effects on the corrosion rate of carbon steel. Compared with Table 13, it can be seen that the amount of nutrient solution had a negative effect on the corrosion rate of carbon steel, while the amount of aeration had a positive effect on the corrosion rate of carbon steel. Reducing the amount of nutrient solution and increasing the aeration rate are beneficial to slow down the corrosion of carbon steel. Similarly, the residual analysis of the full-factor experimental results shows that the model was generally effective and conformed to the normal distribution.

Table 12
Variance analysis of all-factor test of carbon steel corrosion in circulating cooling water

Item	Freedom	Adj. SS	Adj. MS	*F*	*P*
Model	6	0.000409	0.000068	19.55	0.017
Linearity	3	0.000394	0.000131	37.62	0.007
A	1	0.000323	0.000323	92.52	0.002
B	1	0.000014	0.000014	4.13	0.135
C	1	0.000057	0.000057	16.21	0.028
Two-factor interaction	3	0.000016	0.000005	1.49	0.376
AB	1	0	0	0.14	0.734
AC	1	0.000014	0.000014	3.99	0.14
BC	1	0.000001	0.000001	0.33	0.604
Error	3	0.00001	0.000003		
Bending	1	0.00001	0.00001	30.02	0.032
Mismatching	1	0	0	0.51	0.605
Pure error	1	0	0		
Sum	9	0.00042			

In order to further study the optimum process conditions of microbial method for corrosion inhibition effect in circulating cooling water, the test process was optimized as follows. The factors that had significant effect, nutrient solution dosage and aeration rate, were used for re-fitting the model according to the above operation. Through statistical variance analysis, the *P*-values of nutrient solution dosage and aeration rate were 0 and 0.017, respectively, both of which were less than 0.05, which still had significant effects on the corrosion rate of carbon steel. The *P*-value of the bending term was 0.451, which indicates that the model has bending phenomenon. The *P*-value of missing term was 0.184 (>0.05), indicating there was no obvious difference between the predicted value and the experimental value, and the model selection is appropriate. Furthermore, the effect coefficient of carbon steel corrosion test was obtained by statistical analysis. The effect of nutrient solution dosage on carbon steel corrosion rate was negative, and the effect of aeration rate on carbon steel corrosion rate was positive. Reducing nutrient solution dosage and increasing aeration rate were beneficial to slow down carbon steel corrosion.

Comparing the regression analysis tables of the fitting models before and after the comprehensive impact factor optimization, Table 14 is obtained. It can be seen that the *R*-sq. (adjustment) after optimization increased from 92.52% to 94.8%, indicating that the optimized model is obviously better than that before optimization. The obtained final regression equation is:

$$Y = 0.03159 - 0.000318A - 0.536B + 0.002659C \tag{2}$$

where Y is the calcium hardness, A is the nutrient solution dosage and C is the aeration amount.

The residual normality test indicated that the residual distribution conformed to the normal distribution and the model was effective. The contour map of nutrient solution dosage and aeration rate were further plotted (Fig. 7). It can be seen that the corrosion rate of carbon steel decreased

Table 13
Table of all-factor test effect coefficient of carbon steel corrosion in circulating cooling water

Item	Effect	Coefficient	Coefficient standard error	*T*	*P*	Variance expansion factor
Constant	0.027384	0.000591	46.37	0		
A	–0.0127	–0.00635	0.00066	–9.62	0.002	1
B	–0.00268	–0.00134	0.00066	–2.03	0.135	1
C	0.005318	0.002659	0.00066	4.03	0.028	1
AB	–0.00049	–0.00025	0.00066	–0.37	0.734	1
AC	0.002637	0.001319	0.00066	2	0.14	1
BC	–0.00076	–0.00038	0.00066	–0.58	0.604	1

Table 14
Regression analysis table of carbon steel corrosion test of optimized circulating cooling water

	Before deletion	After deletion
S	0.0018677	0.0015564
R-sq.	97.51%	97.11%
R-sq. (Adjustment)	92.52%	94.80%
R-sq. (Prediction)	74.44%	91.86%

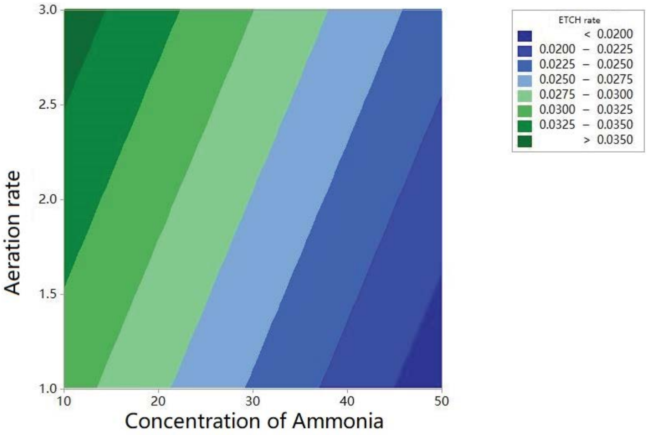

Fig. 7. Isoline diagram of nutrient solution dosage and aeration rate of carbon steel corrosion test of optimized circulating cooling water.

with the increase of ammonia concentration. However, with the increase of aeration rate, the corrosion rate of carbon steel increased. Therefore, increasing the rate of aeration and reducing the amount of nutrient solution can slow the corrosion of carbon steel. To sum up, the microbial treatment method can effectively slow down the corrosion of circulating cooling water, and when the aeration amount is 1 L/min, the dosage of nutrient solution is 0.7‰, lowest carbon steel corrosion rate can be achieved.

In addition, we used the same test process to study the corrosion rate of stainless steel, and the results also show that reducing the amount of nutrient solution and increasing the rate of aeration can slow down the corrosion rate of stainless steel.

3.3. Dynamic simulation test verification

Since the influences of microbial method on scale inhibition and corrosion inhibition effect were analyzed, and the optimum technological conditions of microbial treatment method were determined. In order to further verify the actual effect of microbial method for circulating cooling water treatment, a dynamic simulation experiment was carried out for 18 d with the same circulating cooling water sample, and the change of concentration ratio is shown in Fig. 8.

In the first stage, the concentration increased to five times the initial concentration. From the first day to the 15th day, the outlet temperature was basically stable, the Cl^- index of the circulating water decreased, the total alkalinity and conductivity indexes increased first and then decreased, hardness and Ca^{2+} were basically unchanged, and gradually increased from the 10th day. During this period, ΔACa was less than 0.14, indicating that the circulating water did not scale, and the concentration ratio reached 5.0 on the 15th day.

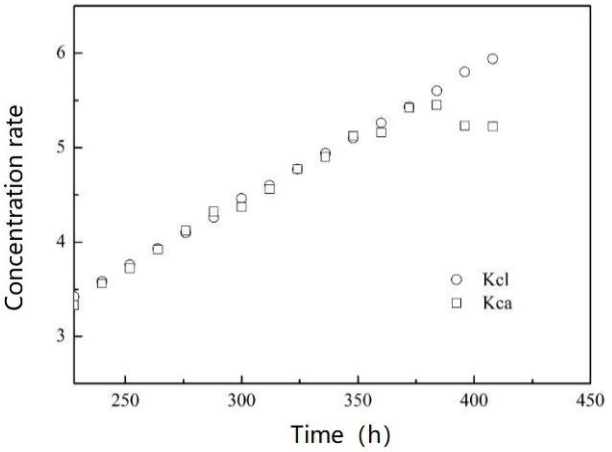

Fig. 8. Concentration ratio diagram of dynamic test of circulating cooling water.

The second stage lasted from the 15th to 18th day, and the outlet temperature was basically stable during the test. The Cl^-, hardness (YD), Ca^{2+}, phenolphthalein alkalinity (PA), methyl orange alkalinity (total alkalinity) (MA) and total dissolved solids (DD) of the circulating water were 341.8–388.9 mg/L, 39.17–45.5 mmol/L, 23.55–25.05 mmol/L, 0.7–0.71 mmol/L and 2,499–2,624 mmol/L, respectively.

Carbon steel (20#), SS316, SS304 and brass were also tested with the same test process. The results showed that SS316 and SS304 stainless steel specimens had only slight weight loss, and the average corrosion rates of the two specimens were 0.00127 and 0.00144 mm/a, respectively. There was only a slight weight loss of the brass test piece, and the average corrosion rate was 0.00152 mm/a. The average corrosion rates of stainless steel specimens of SS316 and SS304 and brass specimens were all lower than that required by national standard (<0.005 mm/a); In contrast, the corrosion of 20# carbon steel specimen was relatively serious, and the average corrosion rate was 0.02197 mm/a, but it was still lower than that required by national standard (<0.075 mm/a).

To further illustrate the advantages of microbial method in the treatment of circulating cooling water, the traditional chemical method was utilized for comparison, and the results are shown in Table 15. It can be seen that, compared with the chemical method, the concentration ratio of microbial method was higher, and the pH value varied from 8.19 to 8.66, which was lower than that of chemical method. It shows that microbial method can influence and adjust the pH value of the system, thus achieving better scale and corrosion inhibition.

To sum up, compared with the traditional chemical method, microbial method can achieve the target of scale inhibition and corrosion inhibition at higher concentration ratio, thus increasing the concentration ratio of circulating water, saving water resources and reducing operating costs.

Table 15
Comparison between microbial method and traditional chemical process method

Number	Item	Microbial method	Chemical method
1	Concentration ratio	3.11~5.4	1.68~1.82
2	Conductivity (us/cm)	1,891~2,624	1,310
3	pH	8.19~8.66	8.68
4	Ca^{2+} (mmol/L)	14.3~25.05	7.6~8.2
5	Cl^- (mg/L)	274.7~397.8	118~124
6	Total hardness (mmol/L)	23.08~45.5	13.0~13.6

4. Conclusions

Circulating cooling water system are some problems such as scaling and corrosion. In this study, water from circulating cooling system of a 300 MW thermal power plant in China was used to study the effect of microbial treatment in scale inhibition and corrosion inhibition of circulating cooling water. The results indicated that microbial method can address the scaling and corrosion problems of circulating cooling water, and the effect of nutrient solution dosage on calcium hardness is positive, while the interaction between nutrient solution dosage and aeration rate has negative effect. When ammonia concentration is 10–50 mg/L and aeration rate is 1–3 L, the minimum calcium hardness is 18.3 mmol/L. However, reducing nutrient solution dosage and increasing aeration rate are beneficial to slow down corrosion rate. The ammonia concentration is 10–50 mg/L and aeration rate is 1–3 L, the minimum corrosion rates are 0.01552 and 0.00110 mm/a, respectively. The microbial method can achieve the goal of low scaling and low corrosion at high concentration ratio, and the highest concentration ratio can reach 5.4. Microbial treatment process has advantages on scale inhibition and corrosion inhibition, but the environmental ecology, molecular biology, microbial genomics and other disciplines should be integrated to investigate the mechanism how different strains affect water quality.

Acknowledgments

This project was financially supported by the National Natural Science Foundation of China (grant number 51974279), the National Key Research & Development Program of China [grant numbers 2018YFC18018, 2018YFC18027], KeJunPing [2018] No. 159, the Guangxi Scientific Research and Technology Development Plan [grants numbers GuikeAB16380287, GuikeAB17129025], GRINM Science and Development [grants number 2020 No 75], which are greatly appreciated.

References

[1] X.X. Zhang, J.G. Liu, Y. Tang, X. Zhao, H. Yang, P.W. Gerbens-Leenes, M.T.H. van Vliet, J.Y. Yan, China's coal-fired power plants impose pressure on water resources, J. Cleaner Prod., 161 (2017) 1171–1179.

[2] J.H. Yao, H.H. Ge, Y. Zhang, X.J. Wang, S.Y. Xie, K. Sheng, X.J. Meng, Y.Z. Zhao, Influence of pH on corrosion behavior of carbon steel in simulated cooling water containing scale and corrosion inhibitors, Mater. Corros., 71 (2020) 1266–1275.

[3] Y. Yang, J.Y. Li, Q.Y. Gu, X.T. Yuan, Study on microbial corrosion inhibition of carbon steel in circulating cooling water system, IOP Conf. Ser.: Earth Environ. Sci., 2021 692 032108.

[4] H.H. Ge, J.T. Tao, X.M. Gong, C.J. Wei, X.M. Xu, Influence of electromagnetic treatment on corrosion behavior of carbon steel and 316l stainless steel in simulated cooling water, Adv. Mater. Res., 347–353 (2012) 3135–3138.

[5] H. Khani, R. Arefinia, Inhibition mechanism of nitrite on the corrosion of carbon steel in simulated cooling water systems, Mater. Corros., 69 (2018) 337–347.

[6] Kh. Rahmani, Reducing water consumption by increasing the cycles of concentration and considerations of corrosion and scaling in a cooling system, Appl. Therm. Eng., 114 (2017) 849–856.

[7] H. Kumar, R.S. Chaudhary, Influence of sodium tripolyphosphate (STPP) antiscalant on the corrosion of carbon steel in cooling water systems, Bull. Electrochem., 22 (2006) 289–296.

[8] F. Brânzoi, V. Branzoi, A. Stanca, M. Iordoc, Inhibition Effect of the New Friendly Environment Inhibitors for Anticorrosion Protection of Cooling Water Systems, 18th International Corrosion Congress, Perth, Australia, 2011, pp. 2159–2172.

[9] C.J. He, Z.P. Tian, B.R. Zhang, Y. Lin, X. Chen, M.J. Wang, F.T. Li, Inhibition effect of environment-friendly inhibitors on the corrosion of carbon steel in recirculating cooling water, Ind. Eng. Chem. Res., 54 (2015) 1971–1981.

[10] H.F. Wang, M.D. Gao, Y. Guo, Y.F. Yang, R.B. Hu, A natural extract of tobacco rob as scale and corrosion inhibitor in artificial seawater, Desalination, 398 (2016) 198–207.

[11] B.R. Zhang, C.J. He, C. Wang, P. Sun, F.T. Li, Y. Lin, Synergistic corrosion inhibition of environment-friendly inhibitors on the corrosion of carbon steel in soft water, Corros. Sci., 94 (2015) 6–20.

[12] Y.X. Zhao, D. Liu, W.L. Huang, Y. Yang, M. Ji, L.D. Nghiem, Q.T. Trinh, N.H. Tran, Insights into biofilm carriers for biological wastewater treatment processes: current state-of-the-art, challenges, and opportunities, Bioresour. Technol., 288 (2019) 121619, doi: 10.1016/j.biortech.2019.121619.

[13] C.M. Chen, Y. Wang, S.T. Liu, R.R. Feng, X.J. Gu, C.X. Qiao, Research on the application of compound microorganism preparation in reusing urban reclaimed water in circulating cooling water system, Water Sci. Technol., 80 (2019) 1763–1773.

[14] A.A. Beni, A. Esmaeili, Biosorption, an efficient method for removing heavy metals from industrial effluents: a review, Environ. Technol. Innovation, 17 (2020) 100503, doi: 10.1016/j.eti.2019.100503.

[15] S.-H. Chien, I. Chowdhury, M.-K. Hsieh, H. Li, D.A. Dzombak, R.D. Vidic, Control of biological growth in recirculating cooling systems using treated secondary effluent as makeup water with monochloramine, Water Res., 46 (2012) 6508–6518.

[16] T. Lundstedt, E. Seifert, L. Abramo, B. Thelin, Å. Nyström, J. Pettersen, R. Bergman, Experimental design and optimization, Chemom. Intell. Lab. Syst., 42 (1998) 3–40.

[17] Touir, A. Koulou, M. Chahboune, Y. El Kacimi, H. Larhzil, Eco-friendly tri-sodium citrate as corrosion inhibitor for mild steel in synthetic cooling water system, J. Basic Appl. Sci., 16 (2020) 9–19, doi: 10.29169/1927-5129.2020.16.02.

[18] R. Touir, M. Cenoui, M. El Bakri, M. Ebn Touhami, Sodium gluconate as corrosion and scale inhibitor of ordinary steel in simulated cooling water, Corros. Sci., 50 (2008) 1530–1537.

[19] G. Annadurai, Y.L. Lai, J.-F. Lee, Statistical optimization of medium components and growth conditions by response surface methodology to enhance phenol degradation by *Pseudomonas putida*, J. Hazard. Mater., 151 (2008) 171–178.

[20] A. Hribernik, M. Bauman, A. Lobnik, Application of 2^k Factorial Design in Wastewater Decolorization Research, XIX IMEKO World Congress Fundamental and Applied Metrology, Lisbon, Portugal, 2009, pp. 2225–2229.