Analysis of Factors Affecting Magnetic Memory Time of CaCO$_3$ Solutions Based on Orthogonal Experiment

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To investigate the effects of magnetic induction intensity, magnetic field treatment time, and solution concentration on the magnetic memory time of CaCO$_3$ solution, an orthogonal experiment was carried out to establish a L$_{16}$(4^5) orthogonal table, and 16 groups of experimental results were obtained on the basis of a self-made electromagnetic water treatment experimental platform. Range and variance analyses were carried out. Experimental results indicated that the main factor affecting the magnetic memory time of CaCO$_3$ solution is the magnetic induction intensity and the effect is significant. The magnetic field treatment time and solution concentration have little effect on the magnetic memory time. In addition, optimum experimental conditions were obtained. When a CaCO$_3$ solution of 2 mmol/L concentration was treated for 36 h with a magnetic induction intensity of 300 Gs, the longest magnetic memory time (about 5600 min) was observed. These research results provide the theoretical basis for the selection of subsequent experimental parameters.

1. Introduction

Fouling is a serious problem in industrial heat transfer equipment, which can easily deposit on a heat transfer surface. Fouling deposition reduces the heat transfer efficiency and increases the power consumption of the equipment and energy generation costs. CaCO$_3$ is the most common fouling constituent in industrial circulating cooling water heat exchange.[1] A 0.8 mm layer of CaCO$_3$ fouling can increase energy use by about 10%.[2] Many chemical and physical methods have been adopted to prevent or mitigate fouling. Chemical methods, such as lime softening and scale inhibitors, are effective. However, these methods have disadvantages, including high cost, water pollution, and chemical residues. Physical methods, such as the application of magnetic and electromagnetic fields, can also solve the fouling problem. In particular, electromagnetic fouling prevention technology has attracted considerable attention in recent years because of its simple operation, low cost, and nontoxicity.[3–5] However, the mechanism of such technology has not been clarified yet.

With the further development of electromagnetic fouling prevention technology, numerous studies indicated that the magnetic field affects the physical and chemical properties of water or solution in different degrees.[6] Moreover, the effect will not disappear immediately after the magnetic treatment is stopped. This phenomenon is called the magnetic memory effect and the holding time is called the magnetic memory time, which can be used to evaluate the effect of magnetic treatment.[7]

Previous studies have described the magnetic memory time.[8–10] Higashitani *et al.* investigated the effects of magnetic exposure on the zeta potential and diffusivity of polystyrene latex particles. It was found that magnetic exposure decreased the zeta potential and the magnetic effect remained for at least six days.[11] Barrett and Parsons conducted experiments to assess the effect of magnetic treatment on the $CaCO_3$ precipitate. They found that the magnetic effect is maintained for at least 60 h after exposure, and magnetic exposure exerts a greater effect on Na_2CO_3 than on $CaCl_2$.[12] Mahmoud *et al.* used a permanent magnet of 8000 Gs as the magnetic treatment device to investigate the effect of magnetic treatment on the fouling power of hard water. Their experimental results showed that the fouling potential of the treated water was significantly inhibited by the applied magnetic field, and that the anti-fouling properties of the treated water were retained for approximately three days after the magnetic treatment.[13] Azoulay studied the change in the surface tension of pure water treated with a magnetic field of 0.12 T and found that the surface tension of pure water increased after magnetic treatment and could be maintained for 210 min.[14]

According to the above studies, the magnetic memory time is different because of different experimental conditions. There are few reports on the magnetic memory time of $CaCO_3$ solution. In this study, on the basis of a self-made electromagnetic water treatment experimental platform, an orthogonal experiment of three factors and four levels was designed to investigate the effects of magnetic induction intensity, magnetic field treatment time, and solution concentration on the magnetic memory time of $CaCO_3$ solution.[15] The optimum experimental conditions based on the experimental platform were found to maximize the magnetic memory effect, which can provide effective parameters for subsequent experiments.

2. Materials and Methods

2.1 Facility

Figure 1 shows the electromagnetic water treatment experimental platform, which consists of a thermostatic water tank, a circulating water pump, an electromagnetic water treatment device, a motor agitator, a heating rod, and an HQ14d conductivity meter. The electromagnetic water treatment device includes an electromagnetic signal generator and a treatment chamber. The electromagnetic signal generator outputs an alternating square wave voltage of 1 kHz, which can generate an axial alternating electromagnetic field in the treatment chamber where the test solution was treated.[16] The magnetic induction intensity is determined by changing the output current of the electromagnetic signal generator. The test solution was pumped from the thermostatic water tank through the treatment chamber and then returned to the
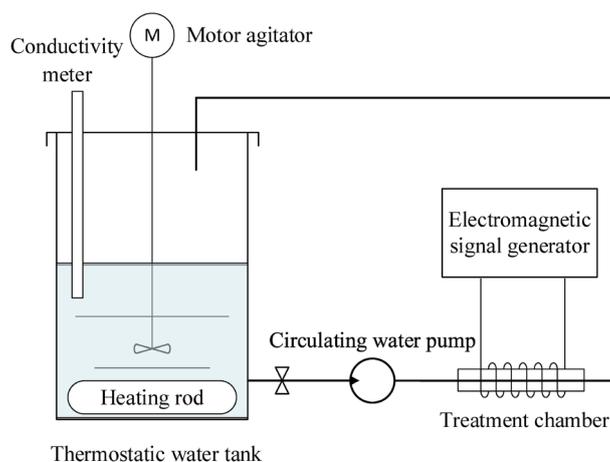
Fig. 1.   (Color online) Electromagnetic water treatment experimental platform.

thermostatic water tank, forming a closed cycle. The test solution is 10 L of $CaCO_3$ solution.
The thermostatic water tank temperature was maintained at 30 ± 0.1 °C. The flow velocity was
stabilized at 0.2 m/s. The specific parameters are shown in Tables 1 and 2.

2.2   Method

In the experimental research, if there are only a few factors involved, it is easier to design,
implement, and analyze the experiment. However, in some experiments, there are many factors
that have a significant effect on the experimental indicator. If all experiments are carried
out, the experimental process is tedious. Therefore, the orthogonal experimental design is a
method of analyzing multiple factors based on the orthogonal table. Some representative level
combinations are selected from all level combinations to carry out experiments. The analysis
of partial experimental results can reflect the situation of all experiments. At the same time,
the optimal level combination and the effect of each factor on the experimental indicator can be
determined.

The selection principle of the orthogonal table requires that each level selected in any
column should appear and the number of times should be equal to include all levels of all factors
in partial experiments. Furthermore, all possible combinations of all levels between any two
columns in the orthogonal table should appear, so that the experimental combination between
any two factors is a comprehensive experiment. To reduce the number of experiments without
affecting the accuracy of experimental results, a small-scale orthogonal table should be selected
on the premise of considering the coupling effect between various factors. In this study, three
factors were selected in the experiment on investigating the magnetic memory time of $CaCO_3$
solution, namely, magnetic induction intensity (factor A), magnetic field treatment time (factor B),
and solution concentration (factor C). Four levels were selected for each factor. The magnetic
induction intensities were 100, 200, 300, and 400 Gs. The magnetic field treatment times were
12, 24, 36, and 48 h. The solution concentrations were 2, 4, 6 and 8 mmol/L, as shown in Table 3.

Table 1
Equipment parameters.

Equipment	Parameter
Thermostatic water tank	0.285 m × 0.285 m × 0.255 m
Conductivity meter	HQ14D
Circulating water pump	GP-3360, 7 W
Heating rod	PY-SM5 (LCD), 1500 W
Motor agitator	JW7114, 370 W

Table 2
Experimental parameters.

Experimental condition	Parameter
Solution volume	10 L
Solution temperature	30 ℃
Flow velocity	0.2 m/s
Frequency	1 kHz
Agitation speed	300 r/min

Table 3
Level factor table.

Level	Factor		
	Magnetic induction intensity (A) (Gs)	Magnetic field treatment time (B) (h)	Solution concentration (C) (mmol/L)
1	100 (A1)	12 (B1)	2 (C1)
2	200 (A2)	24 (B2)	4 (C2)
3	300 (A3)	36 (B3)	6 (C3)
4	400 (A4)	48 (B4)	8 (C4)

On the basis of the above factors and levels, the $L_{16}(4^5)$ orthogonal table is determined, in which the first column is the experimental serial number, and the second, third, and fourth columns are factors. In addition, to make the experiment more accurate, the fifth and sixth columns are errors, and the last column is the experimental indicator, namely, the magnetic memory time, as shown in Table 4. All experiments were carried out according to the orthogonal table, and the experimental results of each group were recorded.

2.3 Experimental procedure

Deionized water (10 L) was poured into the thermostatic water tank. The heating rod, circulating water pump, and motor agitator were turned on. When the temperature of the thermostatic water tank was stable at 30 ℃ and the flow velocity was stable at 0.2 m/s, the electromagnetic water treatment device was turned on. After the magnetic treatment was completed, the electromagnetic water treatment device was turned off. Then, 0.5 L of deionized water was taken out from the thermostatic water tank to configure the corresponding concentrations of the Na_2CO_3 and $CaCl_2$ solutions, which were mixed and poured into the thermostatic water tank. The magnetic induction intensity, magnetic field treatment time, and solution concentration of each group are shown in the orthogonal experimental table. The conductivity of the $CaCO_3$ solution was measured online every 5 min using a conductivity meter. When the conductivity was stable for a period of time, the experiment was completed. Each experiment was repeated thrice. According to the above experimental steps, 16 groups of experiments in the orthogonal experimental table were completed, and the experimental data were recorded and filled in the orthogonal table.

Table 4
Orthogonal experiment table.

Serial number	Magnetic induction intensity (Gs)	Magnetic field treatment time (h)	Solution concentration (mmol/L)	Error 1	Error 2	Experimental indicator
1	100	12	2	D1	E1	Y1
2	100	24	4	D2	E2	Y2
3	100	36	6	D3	E3	Y3
4	100	48	8	D4	E4	Y4
5	200	12	4	D3	E4	Y5
6	200	24	2	D4	E3	Y6
7	200	36	8	D1	E2	Y7
8	200	48	6	D2	E1	Y8
9	300	12	6	D4	E2	Y9
10	300	24	8	D3	E1	Y10
11	300	36	2	D2	E4	Y11
12	300	48	4	D1	E3	Y12
13	400	12	8	D2	E3	Y13
14	400	24	6	D1	E4	Y14
15	400	36	4	D4	E1	Y15
16	400	48	2	D3	E2	Y16

3. Results and Discussion

3.1 Analysis of experimental results

The reference experiment was carried out firstly with the $CaCO_3$ solution of 7 mmol/L concentration. The Na_2CO_3 and $CaCl_2$ solutions were poured into the thermostatic water tank without the electromagnetic water treatment device to observe the change in conductivity over time (Fig. 2). It can be seen that the conductivity first increased rapidly to its peak, then began to decrease, and finally gradually stabilized in about 100 min. When the Na_2CO_3 and $CaCl_2$ solutions were poured into the thermostatic water tank initially, the ion concentration in the solution increased significantly, which led to the rapid increase in conductivity. However, owing to the formation of $CaCO_3$, the ion concentration decreased, which resulted in a significant decrease in conductivity. When the reaction was complete, the solution reached the stable state and no $CaCO_3$ was formed. Therefore, after 150 min, the conductivity of the solution has little obvious change. The experimental period was approximately 1800 min.

Figure 3 shows the change in the conductivity of the 4 mmol/L $CaCO_3$ solution over time under different working conditions. To better analyze the experimental data, the starting point is determined to be the moment when the conductivity begins to decrease. It can be seen from the figure that the conductivity obviously decreased in the initial stage, as observed in the reference experiment. Then, the conductivity increased gradually and finally stabilized after a period of time. The mechanism of "hydrogen bond fracture" illustrates that after an aqueous solution is treated by a magnetic field for a period of time, the hydrogen bond in the aqueous solution is deformed or even broken, and the agglomerated water molecule cluster splits into small or monomer water molecules, which leads to the increase in the activity of water molecules and the increase in the solubility of salt.
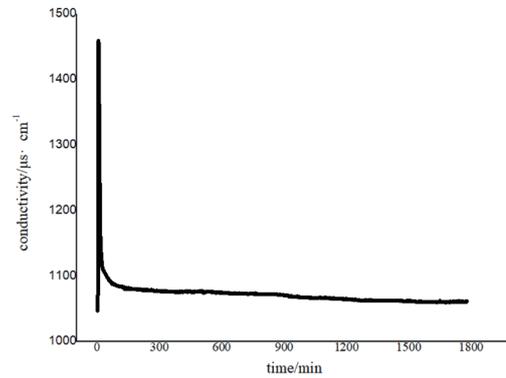
Fig. 2.　Change in solution conductivity without electromagnetic water treatment device.
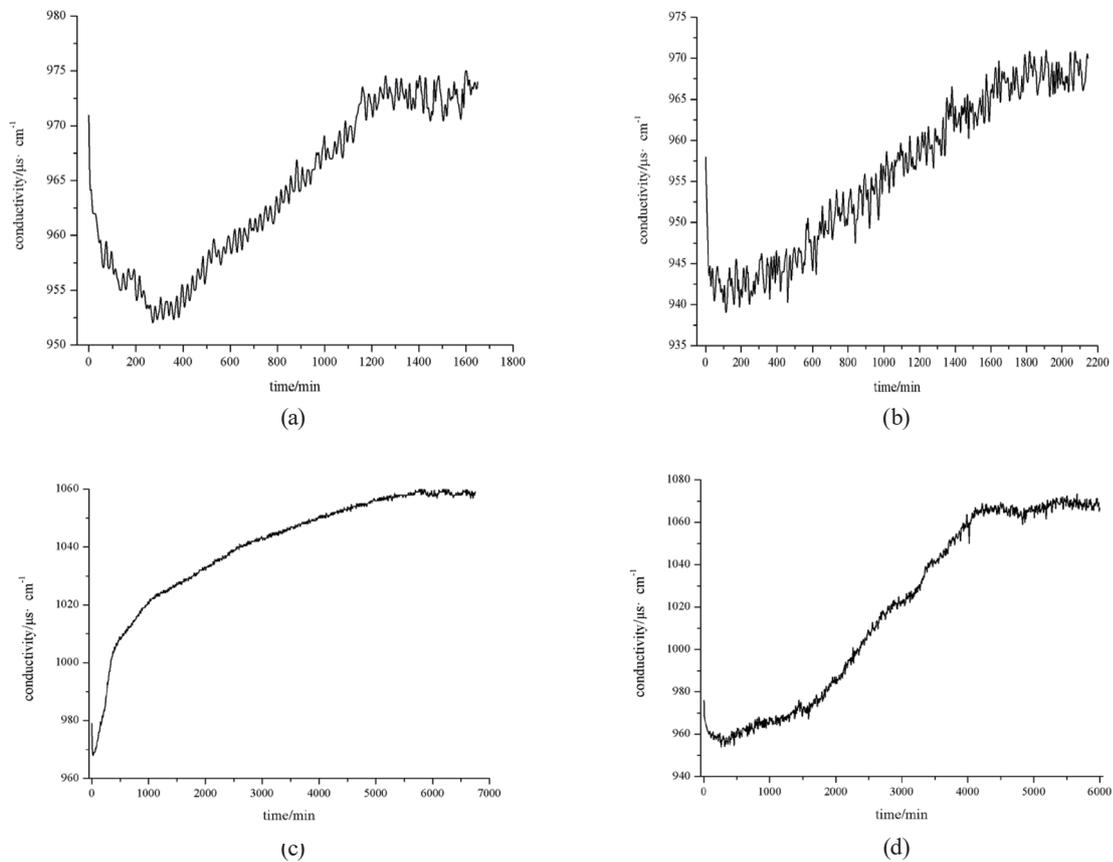

Fig. 3.　Change in conductivity of 4 mmol/L $CaCO_3$ solution over time under different working conditions. (a) 100 Gs magnetic induction intensity for 24 h. (b) 200 Gs magnetic induction intensity for 12 h. (c) 300 Gs magnetic induction intensity for 48 h. (d) 400 Gs magnetic induction intensity for 36 h.

In the experimental process, when the magnetic treatment device was turned off, owing to the existence of the magnetic memory effect, the effect of the magnetic field treatment still existed in the aqueous solution, and the molecular activity of water increased, which increased

the solubility of CaCO₃, so the conductivity of the solution showed an upward trend. However, the magnetic memory effect of the CaCO₃ solution did not always exist. With the development of the experiment, the conductivity tended to be stable gradually after increasing for a period of time. The conductivity of the experimental solution no longer increased, which indicated that the solution no longer had the magnetic memory effect. The magnetic memory time of the CaCO₃ solution is obtained from the starting time to the moment when the conductivity begins to stabilize.

Figure 4 shows the change in the conductivity of the 6 mmol/L CaCO₃ solution over time under different working conditions. The change tendency is basically consistent with that shown in Fig. 3. The conductivity of the solution also decreased at the beginning, then increased gradually, and finally stabilized.

According to the above experiments, the magnetic memory time of the 16 groups of experiments in the orthogonal experiment table is as shown in Table 5.
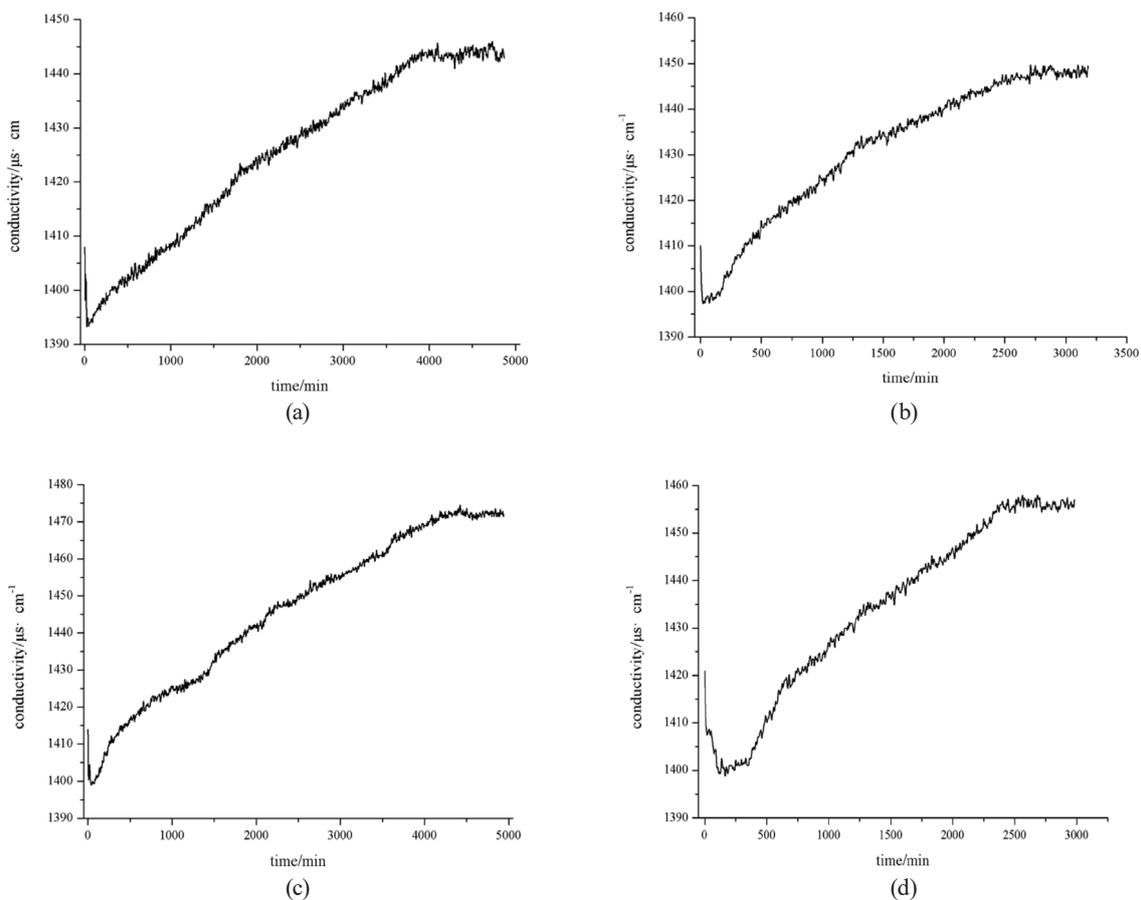

Fig. 4.   Change in conductivity of 6 mmol/L CaCO₃ solution over time under different working conditions. (a) 100 Gs magnetic induction intensity for 36 h. (b) 200 Gs magnetic induction intensity for 48 h. (c) 300 Gs magnetic induction intensity for 12 h. (d) 400 Gs magnetic induction intensity for 24 h.

Table 5
Magnetic memory time.

Serial number	Magnetic memory time (Experimental indicator) (min)	Serial number	Magnetic memory time (Experimental indicator) (min)
1	1500	9	4400
2	1200	10	2300
3	3900	11	5600
4	1300	12	5550
5	1600	13	2200
6	3700	14	2300
7	2900	15	4100
8	2700	16	5100

3.2 Range analysis

To explore the degree of effect of each factor on the experimental indicator in the orthogonal experimental table and determine the optimal level and combination of the experimental factors under the experimental conditions, the orthogonal experimental table is analyzed by range and variance analyses. The range analysis has advantages of easy calculation, simple analysis, and intuitionistic data, which are always used in the theoretical analysis of experimental results.

The experimental results obtained in Table 5 are added into the orthogonal experimental table, and the corresponding parameters are calculated according to the results of the range analysis, as shown in Table 6. k_{ij} is the average of all experimental indicators at level j of factor i. For example, k_{11} is the average magnetic memory time of the four groups of experiments with the magnetic induction intensity of 100 Gs. According to k_{ij}, the optimal level and combination can be obtained. R is the range that reflects the degree of effect of each factor and level on the experimental indicator. The larger the R value, the greater the degree of effect of this factor on the experimental indicator. Therefore, according to R, the degree of effect of each factor on the experimental indicator can be determined.

The experimental indicator of the orthogonal experiment is the magnetic memory time of the $CaCO_3$ solution. The longer the magnetic memory time, the higher the effect of the magnetic field treatment. It can be seen from the range analysis table of the orthogonal experiment that the R of the magnetic induction intensity is the largest, followed by those of the solution concentration and magnetic field treatment time. That is, the magnetic induction intensity has the greatest effect on the magnetic memory time, whereas the effects of the solution concentration and magnetic treatment time on the magnetic memory effect time are basically the same.

The maximum k_{ij} in each column is the optimal level of the corresponding factor, and the optimal level of all factors is the optimal combination under various experimental conditions. According to Tables 5 and 6, the magnetic memory time for the $CaCO_3$ solution of 2 mmol/L concentration, which was treated for 36 h under the magnetic induction intensity of 300 Gs, is the longest (about 5600 min).

Table 6
Range analysis table of orthogonal experiment.

k_{ij} (i = 1, 2, 3)	Magnetic induction intensity (A) (min)	Magnetic field treatment time (B) (min)	Solution concentration (C) (min)
k_{i1}	1975	2425	3975
k_{i2}	2725	2375	3112.5
k_{i3}	4462.5	4125	3325
k_{i4}	3425	3662.5	2175
R	2487.5	1750	1800
Degree of effect		A>C>B	
Optimal level	A3	B3	C1
Optimal combination		300 Gs, 36 h, 2 mmol/L	

3.3 Variance analysis

Although the range analysis of the orthogonal experiment has many advantages, there are a few problems, that is, it is not possible to accurately judge whether the difference in the experimental indicators among different levels of each factor comes from the experimental error or is caused by different levels of each factor. The experimental error cannot be accurately estimated by range analysis, so it is necessary to further explore the experimental results by the variance analysis of the orthogonal experiment. In the variance analysis of the orthogonal experiment, the variation is divided into the following two types: one is caused by the change of factors, and the other is caused by the experimental error. By constructing F statistics and performing the F test, it can be determined whether the effects of factors on the experimental indicators are significant by looking up tables in a certain confidence range. The steps of the variance analysis of the orthogonal experiment are as follows.

(1) Quadratic sum of total deviance

$$SS_T = \sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n} \tag{1}$$

(2) Quadratic sum of column deviance

$$SS_j = \frac{1}{r}\sum_{i=1}^{m} K_{ij}^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n} \tag{2}$$

(3) Degrees of freedom decomposition

$$df_{total} = df_{factor} + df_{empty} \tag{3}$$

(4) Variance

$$MS_{factor} = \frac{SS_{factor}}{df_{factor}}, \; MS_{error} = \frac{SS_{error}}{df_{error}} \tag{4}$$

(5) F statistics

$$F = \frac{MS_{factor}}{MS_{error}} \tag{5}$$

Here, n is the total number of orthogonal experiments, i.e., $n = 16$; m is the number of levels of each factor, $m = 4$; r is the number of repeated experiments of each level, $r = 4$; x_i is the data of the experimental indicator i; K_{ij} is the sum of all experimental indicators at the level j of the factor i.

According to Eqs. (1) to (5), the variance analysis of the orthogonal experimental results was carried out. The quadratic sum of column deviance, the degree of freedom, and the variance were calculated. The total degree of freedom is the number of orthogonal experiments minus 1, and $F_{0.05}$ (3,6) is the result of looking up the table, as shown in Table 7.

According to Table 7, at the significance level of $\alpha = 0.05$, only the F statistical value of the magnetic induction intensity was more than 4.757. Therefore, for the magnetic memory time of the CaCO$_3$ solution, the significance of magnetic induction intensity is the highest, and the magnetic field treatment time and solution concentration are not significant. That is, the magnetic induction intensity has the greatest effect on the magnetic memory time, followed by the magnetic field treatment time and solution concentration.

For the experimental indicator, the longer the magnetic memory time, the higher the effect of the magnetic field treatment. According to the range and variance analyses, under the experimental conditions, when the magnetic field with the magnetic induction intensity of 300 Gs is used to treat the solution, the magnetic field treatment time is about 36 h, and when the solution concentration is not very high, the magnetic memory time of the CaCO$_3$ solution is the longest. Moreover, the changes in magnetic field treatment time and solution concentration have little effect on the magnetic memory time.

Table 7
Variance analysis table of the orthogonal experiment.

Factor	Quadratic sum of column deviance	Degrees of freedom	F statistics	$F_{0.05}$ (3,6)	Factor significance
Magnetic induction intensity (A)	134.38E+05	3	6.096	4.757	*
Magnetic field treatment time (B)	93.58E+05	3	4.245	4.757	
Solution concentration (C)	66.53E+05	3	3.018	4.757	
Error	44.08E+05	6			

4. Conclusions

In this study, on the basis of a self-made electromagnetic water treatment experimental platform, an orthogonal experiment with three factors and four levels was designed to investigate the effects of magnetic induction intensity, magnetic field treatment time, and solution concentration on the magnetic memory time of $CaCO_3$ solution, and the range and variance analyses of the experimental results were carried out. Experimental results indicated that the main factor affecting the magnetic memory time of $CaCO_3$ solution is the magnetic induction intensity, and the magnetic field treatment time and solution concentration are secondary factors. The effect of the magnetic induction intensity on the magnetic memory time is significant, whereas the magnetic field treatment time and solution concentration have little effect on the magnetic memory time. Moreover, optimum experimental conditions were obtained on the basis of the electromagnetic water treatment experimental platform, that is, when the $CaCO_3$ solution of 2 mmol/L concentration was treated for 36 h with the magnetic induction intensity of 300 Gs, the longest magnetic memory time (about 5600 min) was obtained. These research results provide the theoretical basis for the selection of subsequent experimental parameters.

References

1 J. Wang and Y. Liang: Int. J. Heat Mass Transfer. **115** (2017) 774. https://doi.org/10.1016/j.ijheatmasstransfer.2017.07.097
2 X. Wen, Q. Miao, J. Wang, and Z. Ju: Appl. Soft Comput. **57** (2017) 177. https://doi.org/10.1016/j.asoc.2017.03.043
3 A. Fathi, T. Mohamed, G. Claude, G. Maurin, and B. A. Mohamed: Water Res. **40** (2006) 1941. https://doi.org/10.1016/j.watres.2006.03.013
4 X. Xing: Appl. Therm. Eng. **28** (2008) 889. https://doi.org/10.1016/j.applthermaleng.2007.07.006
5 X. Miao, L. Xiong, J. Chen, Z. Yang, and W. He: Water Sci. Technol. **67** (2013) 2784. https://doi.org/10.2166/wst.2013.161
6 J. Wang, Z. Luo, Y. Liang, Z. Li, and L. Wang: Cryst. Res. Technol. **53** (2018) 1. https://doi.org/10.1002/crat.201700188
7 B. Deng and X. Pang: Chinese Sci. Bull. **52** (2007) 3179. https://doi.org/10.1007/s11434-007-0430-7
8 G. Zhu, G. Zhu, and J. Li: J. Henan Univ. Sci. Tchnol. Nat. Sci. **27** (2006) 79. https://doi.org/10.3969/j.issn.1672-6871.2006.01.024
9 X. Zhang, Y. Wang, C. Wang, C. Su, Z. Li, and X. Chen: IEEE Trans. Cybern. **49** (2019) 2106. https://doi.org/10.1109/TCYB.2018.2826519
10 X. Zhang, Y. Wang, X. Chen, C. Su, Z. Li, C. Wang, and Y. Peng: IEEE Trans. Syst. Man Cybern. Syst. **1** (2018) 1. https://doi.org/10.1109/TSMC.2018.2827101.
11 K. Higashitani, H. Iseri, K. Okuhara, A. Kage, and S. Hatade: J. Colloid Interf. Sci. **172** (1995) 383. https://doi.org/10.1006/jcis.1995.1268
12 R. A. Barrett and S. A. Parsons: Water Res. **32** (1998) 609. https://doi.org/10.1016/S0043-**1354** (97)00277-7
13 B. Mahmoud, M. Yosra, and A. Nadia: Sep. Purif. Technol. **171** (2016) 88. https://doi.org /10.1016/j.seppur.2016.07.027
14 J. Azoulay: World J. Eng. **13** (2016) 20. https://doi.org/10.1108/WJE-04-2016-015
15 X. Qian, X. Ma, Z. Qin, S. Hou, M. Xu, P. Zhang, and Z. Zhu: J. Mech. Eng. **1** (2019) 1. https://kns.cnki.net/kcms/detail/11.2187.TH.20190621.1530.020.html
16 J. Wang, Y. Li, and L. Deng: CIESC J. **66** (2015) 972. https://doi.org/10.11949/j.issn.0438-1157. 20141385

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