Experimental study on the influence of sweep frequency electromagnetic anti-fouling technology on industrial circulating water

Bingcheng Liu, Hao Sun, Ning Liu, Chao Li, Mengmeng Zhang and Wenguang Jia

ABSTRACT

Electromagnetic anti-fouling technology (EAFT) is applied to treat scale in cooling water systems and conductivity, pH and particle diameter in solution are the main performance parameters which can reflect the effect of EAFT. In this paper, a series of experiments are carried out to analyze the change rules of the three parameters in solution, both with and without an EAFT device. The motion law of charged particles in the electromagnetic field is analysed, the electromagnetic anti-fouling technology can accelerate collision and the precipitation of scale ions in solution. The experimental results showed electromagnetic anti-fouling technology can effectively reduce the conductivity and pH in solution, and increase the average particle diameter in solution. The main experimental results are listed as follows: (1) with EAFT, conductivity and pH in solution decrease obviously after 4 hours of circulation, and both of them decrease rapidly in the first hour of the experiment, meanwhile the average particle diameter in solution increases quickly; (2) under four groups of experiments, conductivity and pH in solution drop as the sweep frequency is lower, but the average particle diameter in solution increases.

Key words | conductivity, electronic anti-fouling technology, particle diameter, pH, sweep frequency

Bingcheng Liu
Hao Sun
Ning Liu
Chao Li
Mengmeng Zhang
Wenguang Jia (corresponding author)
Qingdao University of Science and Technology, Songling Road No. 99, Laoshan District, Qingdao City, Shandong Province, China
E-mail: *15764240404@163.com*

INTRODUCTION

Water is an important heat transfer medium for industrial production. Scale ions in water circulate with the water cycle, leading to the combination of the scale ions and the formation of crystal precipitates, and these crystal deposits will eventually adsorb on the inner wall of the pipeline. This will increase thermal resistance and the pressure drop in the pipe, thus reducing the performance of the equipment (Doelman 2014; Nur *et al.* 2014; Kazi *et al.* 2015).

Some traditional chemical methods such as dispersion and chelation can effectively mitigate mineral fouling, but these methods also cause secondary pollution due to acid substance and shorten the life of the equipment eventually. For these reasons, some methods such as electromagnetic anti-fouling technology (EAFT) have recently been developed (Tijing *et al.* 2008; Chai 2011; Piyadasa *et al.* 2017). Since the 1980s, EAFT has developed continuously due to the efforts of numerous researchers. Scholars dealt with bacteria by an impulsive electromagnetic field and found that it destroyed the cell membrane and cell wall of bacteria and thereby kill bacteria (Cho *et al.* 1998; Kim *et al.* 2001; Xuefei *et al.* 2013). Later scholars found that a pulsed electromagnetic field effectively prevented the deposition of scale (Kim & Cho 2011; Trueba *et al.* 2015; Chen *et al.* 2016). Simon & Wang (1997) explored the scaling effect of magnetic field treatment on calcium carbonate in solution, and he set up two sets of experiments including an experimental group in which the pH in solution changed over time and a control group where the pH in solution was kept constant,

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and he found that the scale in the experimental group reduced by 46% but the scale in the control group barely changed, which suggested that the pH in solution played an important role in the process of magnetic field scale inhibition. In order to evaluate the effectiveness of scale inhibitors, Drela *et al.* (1998) provided a method based on measuring the conductivity in solution, and he found this method could determine a quantitative relationship between scale inhibitor concentration and relative supersaturation of scale compounds, which indicated that conductivity in solution can reflect the efficiency of $CaCO_3$ precipitation.

Cho & Choi (1999) explained the change rule of calcium carbonate nucleation with the pulsed electromagnetic fields by using Gibbs free energy, and it was found that only the nucleation that reached the critical size can grow spontaneously, the external electromagnetic pulse changed the motion of ions and molecules in solution, and then increased the collision probability of scaling ions and promoted more nucleation to reach the critical size. Le *et al.* (2010) studied hard water of 350 and 500 ppm, then observed the crystal structure of calcium carbonate by electron microscopy and found that it was different with different hardness: calcium carbonate in solution with EAFT presented as squares and calcium carbonate in solution without EAFT presented as needles. Zhang *et al.* (2016) studied calcium carbonate crystals by scanning electron microscopy and observed that the crystals with EAFT treatment were cubic crystals, suggesting that calcium carbonate crystals with EAFT treatment were calcite crystals, and it was also found that the size of the crystals was larger than those without EAFT treatment. Liu *et al.* (2017) explored how frequencies, number of turns, and winding diameter affect the current in the solenoid coil and magnetic induction intensity in carbon steel pipes. They found that the alternating current and the magnetic induction intensity decreased with increasing frequency, and the drop amplitude decreased as the frequency increased.

In summary, EAFT is an effective way to prevent the formation of scale in solution. Conductivity, pH and particle diameter in solution are the crucial parameters which can reflect the actual scale inhibition effect of EAFT. Frequency is the important output parameter of an EAFT device. So, further investigation on conductivity, pH and particle diameter with respect to different sweep frequencies needs to be carried out.

Accordingly, this paper applies sweep frequency EAFT and designs sweep frequency EAFT device, then explores how sweep frequency affects conductivity, pH and particle diameter in solution. The results of this paper show the change rule of conductivity, pH and particle diameter along with time, all of which not only provide design guidance for the EAFT control unit but also put forward a better output frequency of EAFT.

EXPERIMENT FACILITY AND METHOD

Facility

Figure 1 shows a schematic diagram of the experimental device. It consists of an EAFT control unit, a protective resistor, an oscilloscope, 100 turns of tightly wound coils, and a PVC pipe with a diameter of 100 mm. The two ends of the coil are connected to the control unit. When opening the EAFT control unit, there is a closed loop formed by a tightly wound coil of PVC pipe, a protective resistor and an EAFT control unit, which can produce a time-varying magnetic field inside the pipe (Xing *et al.* 2006). The wire is 5.3 mm in diameter and 0.8 mm in insulation thickness. The model of the oscilloscope is TBS1102 produced by Tektronix and it is 100 MHz in bandwidth, ±3% in vertical precision.

In the experimental group, the output voltage of the EAFT control unit in this experiment is set at 60 V, sweep frequency in the experimental groups are 70 k–75 kHz, 75 k–80 kHz, and 80 k–85 kHz, respectively. The control group is set up in this paper, and the EAFT control unit is closed in the control group.

In this paper, the model of the conductivity tester and pH tester is Seven Excellence^{TM} from Mettler Toledo Company (Switzerland). The test range of the conductivity tester

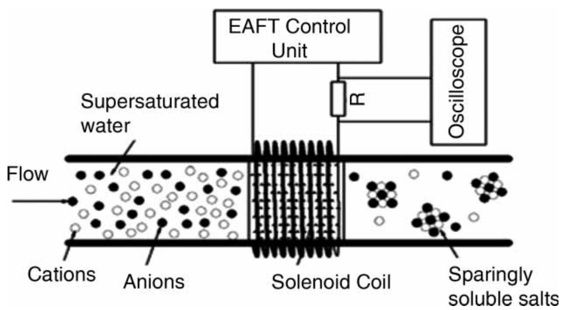

Figure 1 | Schematic diagram of experimental device.

is 0.1–9,999 μS/cm and the measurement accuracy is ±5%. The measuring range of the pH tester is –2 to 20 and the limit of measurement error is ±0.002. The test temperature of the conductivity tester is 25 °C. At the same time, the particle diameter in solution is detected by a laser particle size analyzer (Winner 2003 A, Winner Particle Instrument Company, China) and its range is 0.1–2,000 μm.

Method

Calcium carbonate is used to simulate hard water because it is not easy to dissolve in water and it is also a common form of scale in industrial circulating water systems. In this paper, 55.5 g calcium chloride and 84 g sodium bicarbonate were added to 50 L solution with the mass ratio of 1:2. The water tank temperature was kept at 25 °C by the heating rod. As shown in Figure 2, solution in the water tank enters the test section through the pump and flows back to the water tank after EAFT treatment. The solution in the water tank is replaced and all the experimental equipment is cleaned every 4 hours to prevent the scale from forming in the water tank and the inner pipe, which can affect the experimental results.

At the start of the experiment, an appropriate amount of solution from the water tank was taken via a beaker every 10 minutes. The solution was measured three times by the conductivity tester and pH tester, then the results were averaged and recorded.

After alternating square wave voltage with specified frequency is input on exciting coils, a time varying magnetic field will be generated inside the pipe. When solution flows through the pipe with exciting coils, it is equivalent to cutting the magnetic induction line, and then it will produce induced current and the induced electromotive force according to Faraday's law:

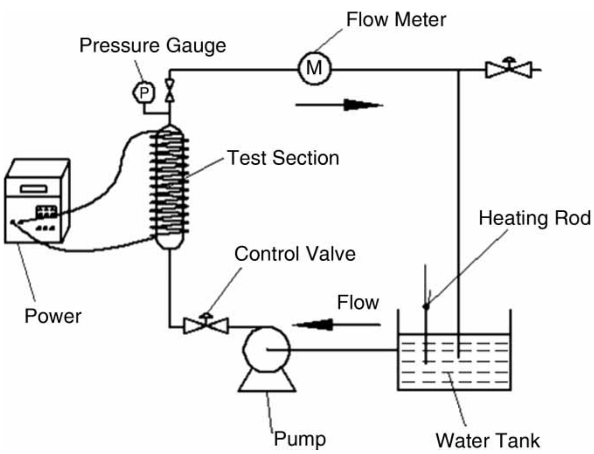

Figure 2 | Experiment platform schematic diagram of winding pulse electromagnetic field treatment system for circulating water.

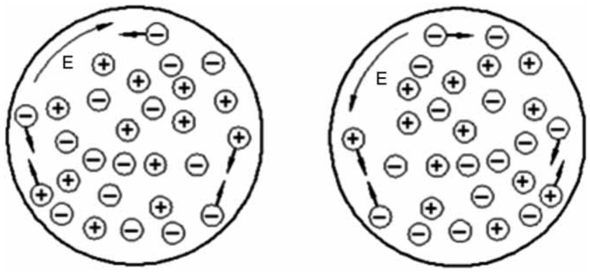

Figure 3 | Schematic diagram of the charged ions motion in an alternating electric field.

$$\int E \cdot dl = -\frac{\partial}{\partial t} \int B \cdot dA \qquad (1)$$

where E is induced electric field intensity vector, l is circumferential vector, B is the magnetic field strength vector, and A is the cross-sectional area.

In the role of induction electromotive force, scale ions in the electromagnetic field are accelerated to move, the movement of calcium ions and carbonate ions are opposite which will accelerate their binding rate. This would speed up the rate of precipitation of calcium carbonate and increase the stability of the crystal size. According to crystal dynamics theory, the process of nucleation from growth to a stable crystal is affected by the ion diffusion rate and the growth of crystals are mainly affected by the supersaturation of the solution without EAFT. With the help of an alternating electric field, the movement of scale ions in solution is mainly dependent on the electric field force and the magnetic force, which could accelerate the diffusion speed and promote the precipitation of calcium carbonate (Figure 3).

RESULTS AND DISCUSSION

Change rule of conductivity in solution along with time under different sweep frequency

As shown in Figure 4, conductivity in solution decreases with time, and conductivity in solution is barely changed after 240 minutes. At the same time, as sweep frequency is lower, the decrease of conductivity is relatively larger. For example, after 240 minutes conductivity in solution without EAFT is gradually stabilized at 4,418 μm/cm, while conductivity in solution under the sweep frequency of 70 k–75 kHz is 4,230 μm/cm. At the same time, as the experiment lasts for 60 minutes, conductivity in solution without EAFT decreases from 4,600 to 4,490 μm/cm. Conductivity in solution under sweep frequency of 70 k–75 kHz decreases from 4,598 to 4,365 μm/cm, which is 125 μm/cm lower than that in solution without EAFT. Conductivity in solution under the sweep frequency of 80 k–85 kHz decreases from 4,599 to 4,445 μm/cm in the first hours, and is finally stable at 4,347 μm/cm. When the sweep range is at 75 k–80 kHz, conductivity in solution in the previous hour decreased from 4,600 to 4,440 μm/cm and is finally stable at 4,285 μm/cm.

The concentration in the initial solution is high, so conductivity in solution is higher too. With sweep voltage inputting in the test section, there would be a time-varying electromagnetic field, and the electromagnetic disturbance makes the charged particles in solution, such as calcium and carbonate ions, accelerated, then it forms precipitation and reduces the number of charged particles and the concentration in solution. Conductivity in solution decreases gradually as the number of charged particles decreases. In the first hour, the number of charged particles in the solution is large, so the collision frequency is higher, and the formation of precipitation is faster. As time passes, the number of charged particles in solution decreases, and the rate of the scale ions collision and precipitation slow down, so the reduction of conductivity is relatively slower.

Change rule of PH in solution along with time under different sweep frequency

As shown in Figure 5, the pH in solution gradually decreases with time. At the same time, pH in solution decreases more quickly at lower sweep frequencies. pH in solution without EAFT and the other three groups gradually stabilize after 240 minutes. For example, pH in solution without EAFT is 7.26 after 1 hour, but under the sweep frequencies of 80 k–85 kHz, 75 k–80 kHz and 70 k–75 kHz, pH in solution is 7.21, 7.14 and 7.08, respectively, all of which are lower than that in solution without EAFT. After 240 minutes, the pH in solution without EAFT is 7.14, but the pH in solution is 7.09, 7.04 and 6.97, respectively, with the sweep frequencies of 80 k–85 kHz, 75 k–80 kHz and 70 k–75 kHz.

In the initial stage of the experiment, the solution is alkaline due to bicarbonate ions in the solution. In the experimental process, the following reaction occurs in solution:

$$Ca(HCO_3)_2 \rightleftharpoons CaCO_3 \downarrow + CO_2 \uparrow + H_2O \tag{2}$$

The action of electromagnetic field accelerates the binding rate of scale ions, so the above reaction (2) proceeds to the right, which will generate carbon dioxide in water and then decrease the pH in solution. As the number of ions decreases, the collision rate of the scale ions and the precipitation decrease, and the decline rate of pH in the solution also slows down, and eventually tends to be stable.

The electromagnetic induction current and induced electromotive force is larger as sweep frequency is lower, which could reduce the collision and binding rate of scale

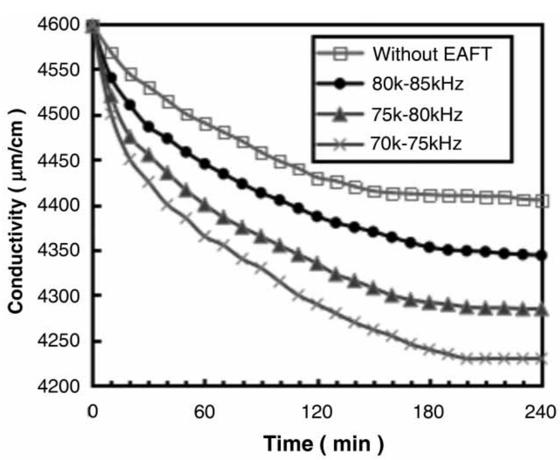

Figure 4 | Change rule of conductivity along with time under different sweep frequency.

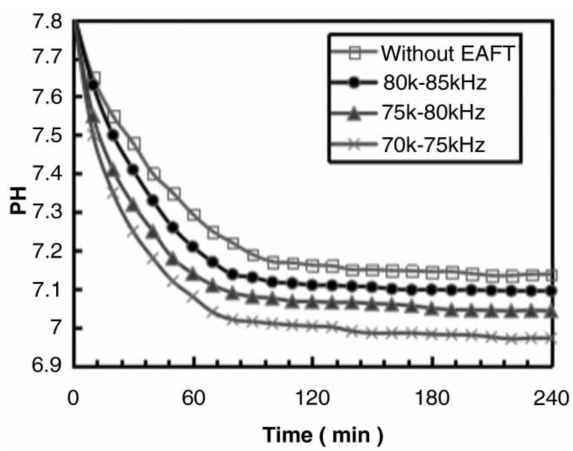

Figure 5 | Change rule of PH in solution along with time under different sweep frequencies.

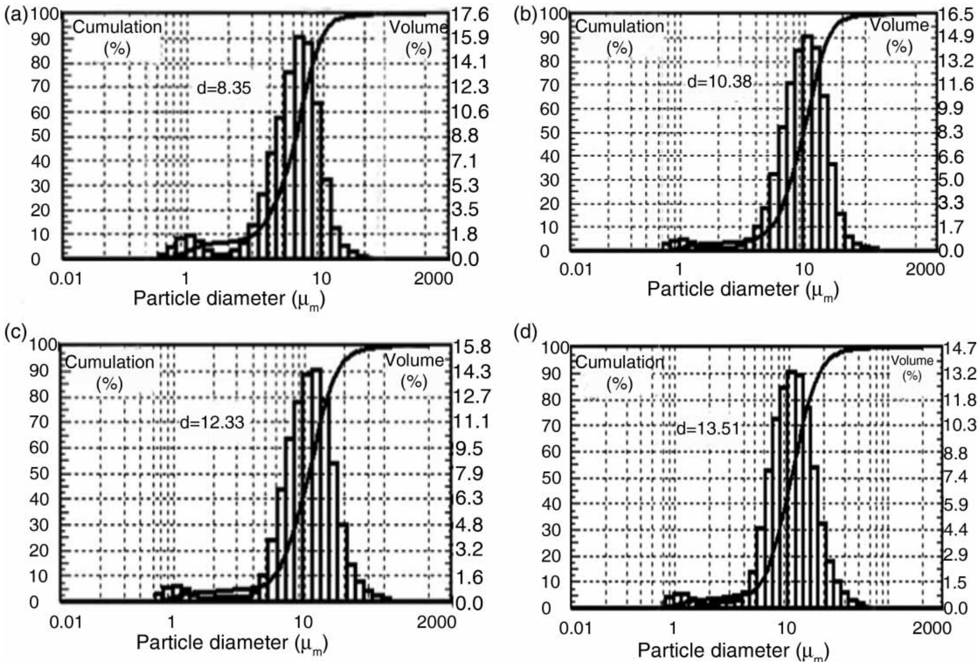

Figure 6 | Particle diameter distribution in solution after 4 hours: (a) without EAFT; (b) under the sweep frequency of 80 k–85 kHz; (c) under the sweep frequency of 75 k–80 kHz; (d) under the sweep frequency of 70 k–75 kHz.

ions and the degree of reaction to the right could be greater, so more calcium carbonate precipitation is generated and carbon dioxide spills from solution, and conductivity and pH in solution decrease gradually.

Distribution of particle diameter in solution after 4 hours of circulation

As shown in Figure 6, after 4 hours of circulation the average particle diameter is 8.35 μm without EAFT, 10.38 μm under the sweep frequency of 80 k–85 kHz, 12.33 μm under the sweep frequency of 75 k–80 kHz and 13.51 μm under the sweep frequency of 70 k–75 kHz. The positive and negative ions move out of order without EAFT, and the formation rate and dissolution rate of calcium carbonate are almost equal. However, with the sweep frequency, the scale ions in solution are accelerated to move, so the rate of collision and the precipitation is quicker under the action of electromagnetic field, which causes the rate of crystal nucleation to be far greater than that without EAFT.

Change rule of average particle diameter in solution along time under different sweep frequency

As shown in Figure 7, the particle size increases over time at different frequencies and tends to be stable after 4 hours. The lower the sweep frequency is, the larger the particle diameter and growth rate is. For example, after 1 hour of experiment, particle diameter increases from 8.217 to 11.2 μm with the sweep frequency of 70 k–75 kHz, the particle size increased from 8.217 to 9.4 μm under the sweep frequency of 80 k–85 kHz, while the particle diameter in solution without EAFT remain at 8.217 μm. This is because the lower the sweep frequency is, the greater the induced electromotive force is, and the collision and binding

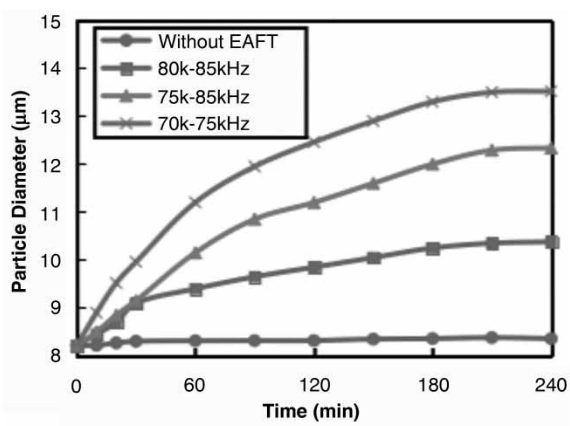

Figure 7 | Change rule of average particle diameter in solution over time under different sweep frequencies.

rate of the scale ions could be quicker, finally increasing the average particle diameter.

CONCLUSIONS

In this paper, an experiment platform of a winding pulse electromagnetic field treatment system for circulating water is built. The motion law of charged particles in the electromagnetic field is analyzed. Then it studies how sweep frequency affects conductivity, pH and the average particle diameter in solution over with time. The main conclusions of the experiment are as follows:

1. Electromagnetic anti-fouling technology can effectively reduce the conductivity and pH, and increase the average particle diameter in solution. In the first hour of the experiment, conductivity and pH in solution decrease most obviously, but the average particle diameter increases most rapidly.
2. Under four groups of sweep frequency in this experiment, conductivity and pH in solution decrease with a lower sweep frequency, but the average particle size increases, indicating that the effect of anti-fouling is best with the sweep frequency of 70 k–75 kHz.

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