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Experimental study on the effect of solenoid coil winding pipe material on electromagnetic anti-fouling effect

Bingcheng Liu, Ning Liu*, Xiangyang Han, Hongsong Li, Wenguang Jia

Qingdao University of Science and Technology, Songling Road No.99, Laoshan District, Qingdao city, Shandong province, China, emails: lnshgan@outlook.com (N. Liu), 1518065921@qq.com (B. Liu), 690786753@qq.com (X. Han), 17862989501@163.com (H. Li), 17860848786@163.com (W. Jia)

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ABSTRACT

The purpose of the present study was to compare the different anti-fouling effects of swept electromagnetic fields on circulating water in PVC pipe and carbon steel pipe. The effects of the PVC pipe and carbon steel pipe on the effectiveness of the electromagnetic anti-fouling (EAF) technology were experimentally studied. Both pipes were the same in terms of diameter, thickness and the number of turns wounds by the coil. The water hardness is 10 mol m^{-3} as $CaCO_3$. Seven different experiments were conducted in this way: one without EAF treatment and six runs with EAF treatment, the six experiments were the hard water in the PVC pipe and carbon steel pipe under three different sweep frequencies electromagnetic field. The three different sweep frequencies were 1–3, 9–11, and 19–21 kHz respectively. The experiment results showed that the anti-fouling effect of EAF applied to PVC pipe is better than that of carbon steel pipe, and when the sweep frequency is 1–3 kHz, the anti-fouling effect is better than others in experiments, the hard water conductivity in the PVC pipe is 83.2 μS/cm less, pH is 0.06 lower, and the average particle diameter is 0.416 μm bigger than the carbon steel pipe; the conductivity is196.5 μS/cm less, pH is 0.179 lower, and the average particle diameter is 1.748 μm bigger than the without EAF treatment, and the gap has an increasing trend.

Keywords: Electromagnetic anti-fouling; PVC and carbon steel pipe; Conductivity; pH; Particle diameter

1. Introduction

The circulating water plays an essential role in heat exchanges, however, circulating water is often hard water. With the evaporation of circulating water, the scaling ions concentration increases and scaling ionic precipitates on the industrial heat exchanger and pipe. Scales are often observed in industry materials include calcium carbonate, calcium sulfate, barium sulfate, silica iron scales and others, all of which occur naturally in water supplies [1]. $CaCO_3$ is the most common form of scale, so it's the subject of the present study.

Once scale builds up on the pipe, it not only increases the overall thermal resistance, which can substantially reduce heat performance but also corrodes the pipe and reduces the service life of the pipe, leading to an increase in operating costs [2–5]. There are two critical points for scaling inhibition. The first point is reducing the concentration of scaling ions, as an excessive concentration of scaling ions leads to crystallization in circulating water. The second point is prohibiting scale adhering to the pipe wall, if scale flows with the circulating water and precipitates in the circulating cistern, it will be easy to exhaust with the sewage. There are many ways to deal with a scale that can attribute to chemical and physical methods [6]. The chemical method usually adds chemical agents in circulating water to reduce the concentration of scale-forming ions or prevent the formation of scale-forming ions to achieve the purpose of anti-fouling.

* Corresponding author.

There is no doubt that the chemical anti-fouling method has high cleaning efficiency and obvious effect. However, chemical agent corrosion not only shortens the life of heat transfer equipment but also deleterious the environment [7–9], so chemical agents should be replaced as soon as possible. The electromagnetic anti-fouling (EAF) technology is a very useful physical method to prevent scales [10]. The electromagnetic field increases the molecular agitation of the scaled ions and water molecules in the circulating water, which not only increases the probability of scale formation but also makes the generated scale is soft and poor adhesion ability makes scale easily be washed away by the water flow within the pipe [11,12].

Bingcheng et al. [13] explored how the output frequency, the number of turns and the diameter of the pipe affect the current in the solenoid coil and the magnetic induction in the carbon steel pipe. They found that the alternating current and magnetic induction decrease with increasing frequency, and the magnitude decreases as the frequency increases. Yong et al. [14] explored the variations in the solution conductivity, pH, and particle diameter with time in the PVC pipe and found that the conductivity, pH, and magnitude decrease with the time, the particle diameter increases with time. To evaluate the effectiveness of scale inhibitors, Drela et al. [15] provided a method based on measuring the conductivity of a solution, which he found to determined the quantitative relationship between the concentration of the scale inhibitor and the relative supersaturation of the scale compound. It shows that the conductivity in the solution can reflect the efficiency of $CaCO_3$ precipitation. All of these studies focus on the solenoid coil wound around PVC pipe or carbon steel pipe; they didn't compare the anti-fouling effect when the materials of the solenoid coil winding pipe are different. This paper was to investigate the different anti-fouling effect of PVC pipe and carbon steel pipe. To compare the anti-fouling effect in PVC pipe with carbon steel pipe, we establish a platform to investigate the change of conductivity, pH, and particle diameter with time under sweep frequency in PVC pipe and carbon steel pipe, and compare the anti-fouling effect by the conductivity, pH and particle diameter with time.

2. Effect of PVC pipe and carbon steel pipe on the electromagnetic field

When the circulating solution flow in the pipe, the EAF control unit produces a time-varying current in the solenoid coil to create a time-varying magnetic field in the pipe, meanwhile, the time-varying magnetic induces an electric field in the pipe, that can explain by Faraday's law:

$$\int E \cdot ds = -\frac{\partial}{\partial t}\int B \cdot dA \tag{1}$$

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

Fig. 1 shows the process of the charged ions influenced by the induced electromagnetic field to form the particle. The Lorentz force increases the molecular agitation of the scaled ions in the circulating water, which not only increases the probability and efficiency of scale formation but also increases the generated soft scale. Poor adhesion ability makes it easily be removed by turbulence and routine blowdowns. Thus, it mitigates precipitation fouling in heat exchangers [11,16].

The movement of charged particles in the electromagnetic field is affected by the Lorentz force; the force can be calculated by:

$$F = \int V\left(pE + J \times B\right)dr \tag{2}$$

where V is the volume of the integral, p is the charge density, J is the current density, and r is the body element.

The induced electromagnetic field provides molecular agitation to charged calcium ions and collides and precipitates bicarbonate ions to form $CaCO_3$ nuclei, see Fig. 1.

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 \downarrow + H^+ + HCO_3^- \tag{3}$$

Cho et al. [17] found that the supersaturated solution forms a large number of nuclei before entering the heat exchanger under the EAF treatment, which reduces the supersaturation of cooling water before entering the heat exchanger, and generating calcium carbonate is calcite with low adhesion and can discharge with the cooling water, therefore, the EAF treatment can achieve the purpose of scale inhibition.

According to the mechanism, the electromagnetic field increased the probability and efficiency of calcium ions and bicarbonate ions collide and precipitate forming $CaCO_3$; therefore, the stronger the electromagnetic field strength is, the more $CaCO_3$ is formed, the anti-fouling effect is better.

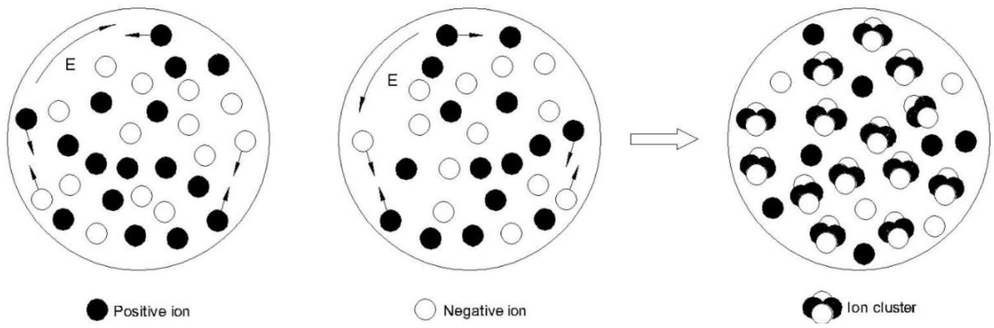

Fig. 1. Schematic diagram of the induced electromagnetic field working to ions motion in the solution.

There is no doubt that the material would affect the distribution of the electromagnetic field. Since only calcium ions and carbonate ions form precipitation in the solution, the conductivity can be used to indicate changes of calcium ions, and the particle diameter is the $CaCO_3$ diameter, and hence we compare the PVC pipe and carbon steel pipe affect the anti-fouling effect by conductivity and average particle diameter.

3. Experimental method

3.1. Material

The schematic diagram of the experimental structure is shown in Fig. 2, which contains the EAF control unit, an oscilloscope, protective resistor, 90 turns of coil tightly around the 100 mm diameter pipe and supersaturated water. The type of the wire was polyvinyl chloride insulated flexible cables with copper core meeting China National Standard where the conductor was 5.3 mm in diameter and 0.8 mm in insulation thickness. The two ends of the winding coil were directly connected to the EAF control unit by a protective resistor, and the EAF control unit can produce a time-varying magnetic field inside the pipe. The model of the oscilloscope is TBS1102 produced by Tektronix, and it was 100 MHz in bandwidth, ±3% in vertical precision.

In the experimental group, the output voltage of the electromagnetic anti-fouling treatment (EAFT) control unit in this experiment set is 9.6 V, sweep frequency in the experimental groups are 1 k–3 kHz, 9 k–11 kHz, and 19 k–21 kHz respectively, and outputs square wave that maximizes the anti-fouling effect. The flow rate of circulating water flowing through the pipe is 0.21 m/s. The control group was set up in this paper; that is, there is no use of EAFT in this group.

In this paper, the model of the conductivity tester and pH tester is Seven Excellence™ from Mettler Toledo Company. The test range of conductivity tester is 0.1–9,999 μS/cm and the measurement accuracy is ±0.5%. The measuring range of the pH tester is –2–20 and the limit of measurement error is ±0.002. The temperature compensation of the conductivity tester is 25°C. At the same time, the particle diameter in solution is detected by a laser particle size analyzer of Winner 2308, which is produced by the Winner Particle Instrument Company of China, and its range is 0.1–2,000 μm and the accuracy and repeatability errors are all less than 3%.

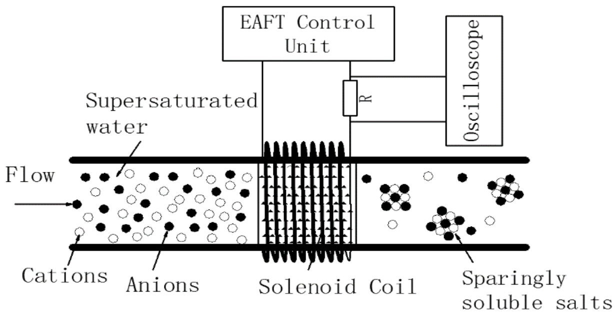

Fig. 2. Schematic diagram of the experimental device.

3.2. Method

We have proved that the 90 turns of coil tightly around the 100 mm diameter pipe are the optimize parameters [12]. From the formula, we can conclude that the material of the pipe and the output frequency will affect the magnetic induction intensity. Therefore, we can compare the anti-fouling effect when the coil winding materials of the pipe are PVC and carbon steel pipe at different sweep frequencies.

Calcium carbonate is one of the main components of scale. To speed up the process of scaling, in this experiment, 111 g $CaCl_2$ and 168 g $NaHCO_3$ were poured into 100 L of distilled water to simulate industrial circulating water with a hardness of 1,000 ppm as $CaCO_3$. The water temperature was controlled at 25°C by the thermostat. Fig. 3 shows the schematic diagram of the fouling test facility in the present study. At the beginning of the experiment, 111 g $CaCl_2$ and 168 g $NaHCO_3$ were separately added to 50 L of water for complete dissolution and poured into the water tank. The hard-aqueous solution in the water tank was sent to the test section by the pump and was treated by the electromagnetic field and then returned to the water tank.

Since the change at the beginning of the experiment is obvious, the conductivity was recorded every 10 min, and the pH and particle diameter were recorded every 20 min in the first hour. 2 h later the conductivity and the pH were recorded every hour, and the particle diameter was recorded every 2 h.

4. Results and discussion

Fig. 4 represents variation in conductivity as a function of time at different frequencies. As time increases, the rate of conductivity decreases more and more slowly in PVC pipe and carbon steel pipe. For example, in the case of 1–3 kHz PVC pipe, the conductivity decreases from 4,503.8 to 4,288.3 μS/cm in the first hour, and the conductivity reduced by 60.7%. The main reason is that the supersaturation of the solution is too high at the beginning, and as the calcium carbonate formed precipitation in the solution, the supersaturation of the solution decreases and the conductivity decreases more and more slowly. At the same time, it can be concluded that the solution conductivity in the PVC

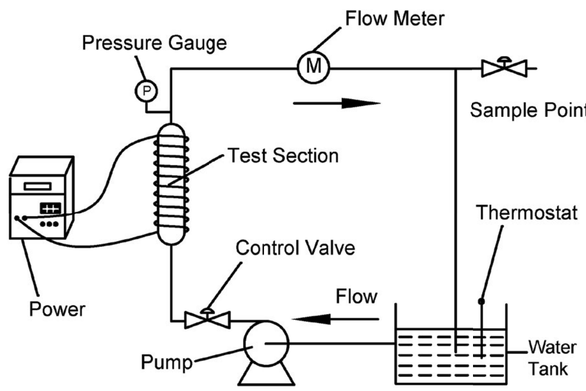

Fig. 3. Schematic diagram of the fouling test facility in the present study.

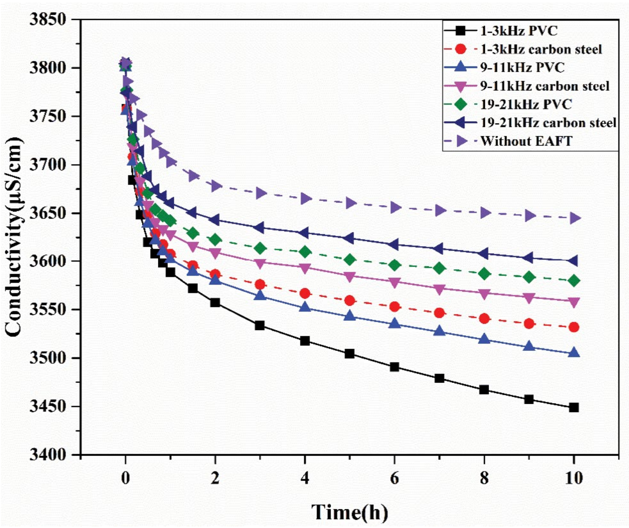

Fig. 4. Variation of conductivity with time under different frequencies.

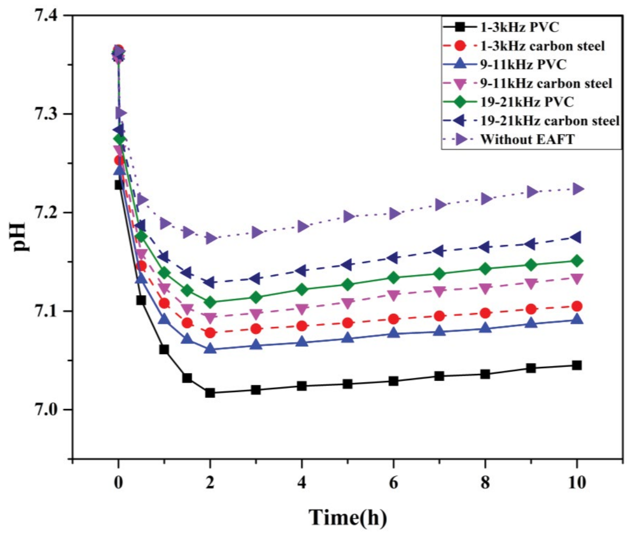

Fig. 5. Variation of pH with time under different frequencies.

pipe is less than the solution conductivity in the carbon steel pipe at the same sweep frequency, it implied that the PVC pipe is better than carbon steel pipe at the same frequency when applied in EAFT system. With EAFT, conductivity is significantly less than that without EAFT, the main reason is that the time-varying electromagnetic field provides necessary molecular agitation to charged mineral ions, accelerating collision and precipitation of calcium and bicarbonate ions, which could result that conductivity declined faster and declined greater. When the frequency is 1–3 kHz, the lowest conductivity suggests 1–3 kHz as the optimal sweep frequency.

Fig. 5 represents variation in pH as a function of time at different frequencies. It can be concluded that the pH rapidly decreases in the first 2 h and reaches the minimum in about 2 h, then slightly rise. The main reason is that the following reactions occur in the solution:

$$CaCl_2 + 2NaHCO_3 \Leftrightarrow CaCO_3 \downarrow + CO_2 \uparrow + 2NaCl + H_2O \quad (4)$$

$$H_2O + CO_2 \Leftrightarrow H_2CO_3 \quad (5)$$

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \quad (6)$$

At the beginning of the experiment, with the precipitation of $CaCO_3$ and the overflow of CO_2, the reaction (4) proceeds to the right, and the CO_2 reacts with water to form H_2CO_3, H_2CO_3 ionize out H^+, which makes solution pH decrease. As the reaction (4) progresses, the rate of generating CO_2 slower and the supersaturation of CO_2 reduced in solution, which makes the reaction (6) proceeds to the left, and thus the solution pH slightly increases.

Fig. 6 represents variation in average particle diameter as a function of time at different frequencies. From Fig. 6, we can conclude that the average particle diameter has the same trend in PVC pipe and carbon steel pipe, as the time increases, the rate of average particle diameter increases and the magnitude decrease with the time. In Fig. 6, the average particle diameter in PVC pipe is bigger than the average particle diameter in carbon steel pipe at same sweep frequency, it implied that the electromagnetic field strength in the PVC pipe is stronger than that in the carbon steel pipe, in other words, PVC pipe is better than carbon steel pipe at the same frequency when applied in the EAFT system. Without the EAFT, the average particle diameter is the smallest, and the average particle diameter is the biggest when the EAFT output sweep frequency is 1–3 kHz. The biggest particle diameter is 18% larger than the smallest particle diameter at 10 h, and the gap has an increasing trend. The main reason is that EAFT significantly lifts the probability and efficiency of the positive and negative ions binding, and the more nucleation makes the nucleus easier augmented. Therefore, the average particle diameter rapidly increases at the beginning, and the growing speed of the average particle diameter becomes slow with the precipitation of calcium carbonate. In Fig. 7a–h, the particle diameter in PVC pipe is significantly bigger than the particle diameter in carbon steel pipe at the same frequency, it can be explained that the induced magnetic field shielded by the carbon steel pipe wall will induce a time-varying current in the pipe wall, and the time-varying current generates a secondary induced magnetic field in the pipe, thereby the wire winding on carbon steel pipe also has an anti-fouling effect. When the current in the pipe wall generates a magnetic field in the pipe, there is a phenomenon of wasting electric energy such as generating heat in the carbon steel pipe, so that the secondary induced electromagnetic field is smaller than the electromagnetic field directly induced in the PVC pipe by the winding coil, and hence the effect is greatly reduced.

As shown in Fig. 8a–d, the variation of the particle diameter 0–10, 10–20, 20–30, and 30–40 μm volume ratio as a function of time. In Fig. 8, the proportion of 0–10 μm gradually decreases; the proportions of 10–20 and 20–30 μm in the average particle diameter gradually increase, and the rate of increases becomes slower; the proportion of 30–40 μm in the average particle diameter gradually increases, and the rate

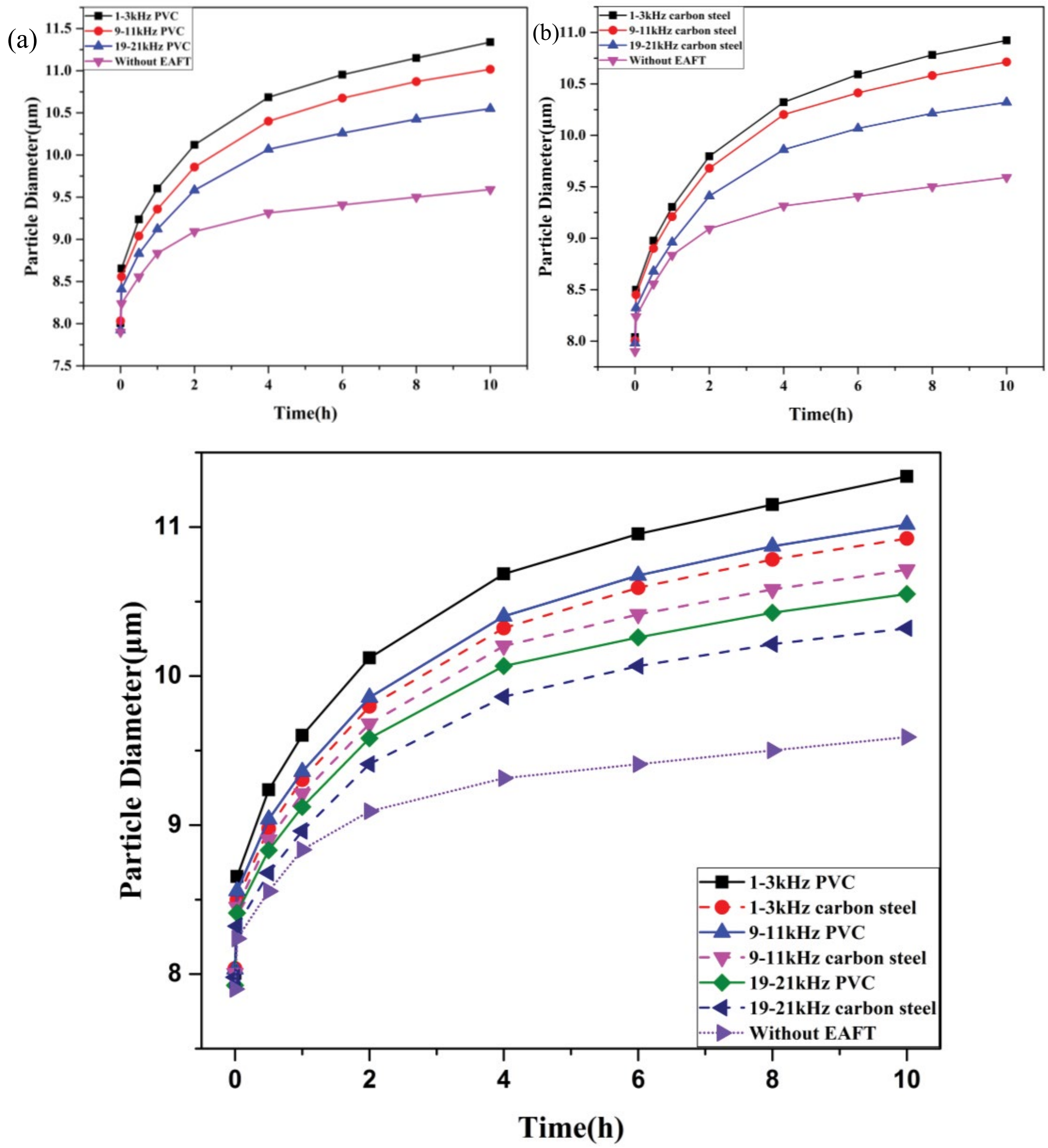

Fig. 6. Variation of average particle diameter with time under different frequencies. (a) Variation of average particle diameter with time in the PVC pipe under different frequencies and (b) variation of average particle diameter with time in the carbon steel pipe under different frequencies.

of increases becomes faster. The proportion of particle diameter 0–10 μm in carbon steel pipe is more than PVC pipe at the same frequency, and with an electromagnetic field, treatment is significantly smaller than that without electromagnetic field treatment; The proportions of particle diameter 10–20, 20–30, and 30–40 μm in carbon steel pipe are smaller than those in PVC pipe at the same frequency, and with an electromagnetic field, treatment is significantly bigger than that without electromagnetic field treatment. From Fig. 8, the proportion of 0–10 μm with the power output frequency of 1–3 kHz in the PVC pipe is the least compared with other frequencies, and the proportions of 10–20, 20–30, and 30–40 μm account for the largest ratio. It proves that the electromagnetic field produced by the EAF treatment promotes the growth of $CaCO_3$ crystals in solution. As Cho [17] reported, the EAF treatment supplied activation energy makes the overall Gibbs free energy negative in sign, and hence the nucleus to continue to grow.

5. Conclusions

In this paper, we built an experiment platform to investigate the different anti-fouling effects of PVC pipe and carbon steel pipe under the swept electromagnetic field. The effect of pipe material and sweep frequency on the anti-fouling effect were expressed by the variation in conductivity, pH and average particle diameter as a function of time. The main conclusions of the experiment are as follows:

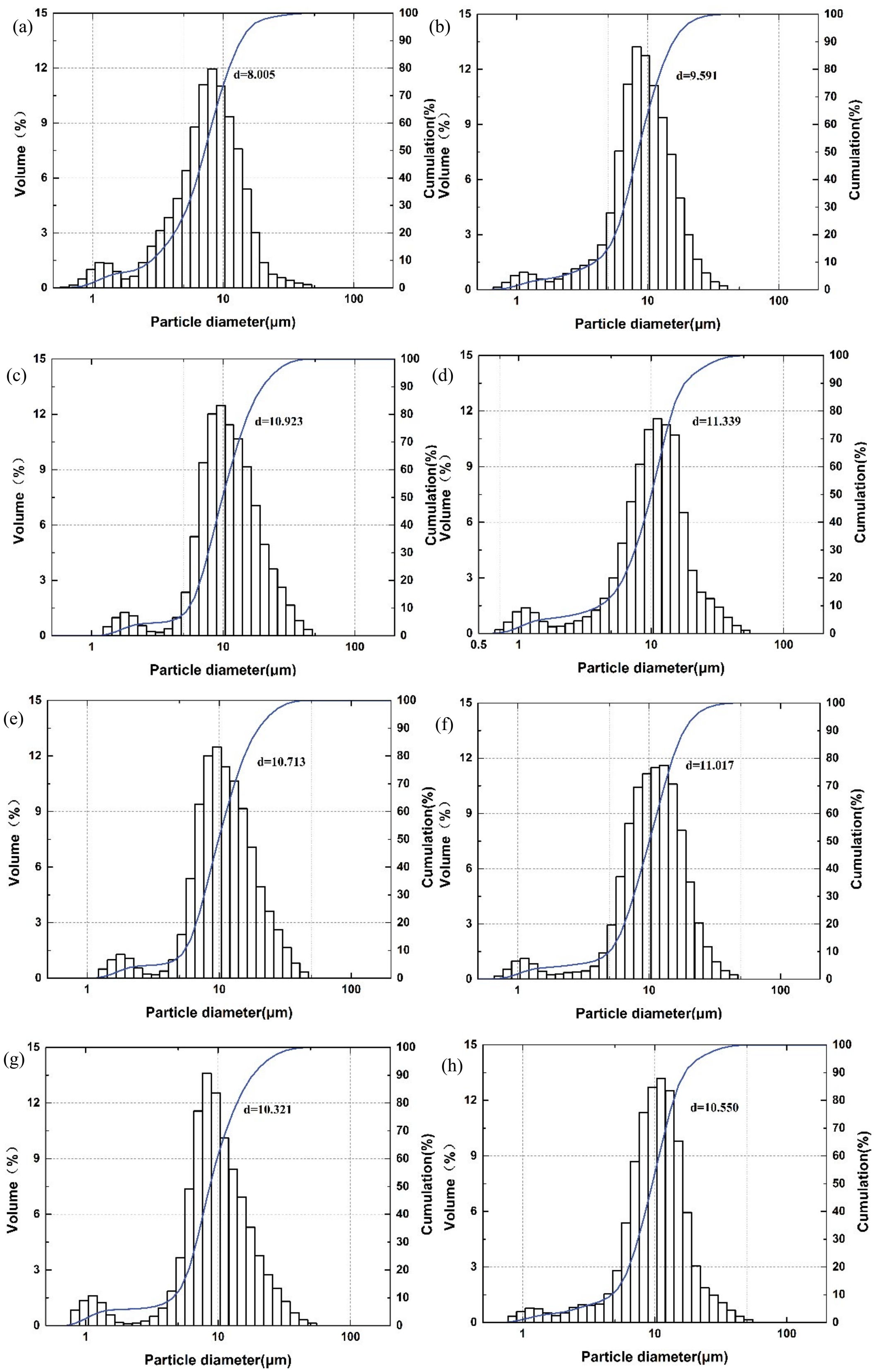

Fig. 7. Particle diameter. (a) Initial particle diameter, (b) without EAFT, (c) sweep frequency of 1–3 kHz in carbon steel pipe, (d) sweep frequency of 1–3 kHz in PVC pipe, (e) sweep frequency of 9–11 kHz in the carbon steel pipe, (f) sweep frequency of 9–11 kHz in the PVC pipe, (g) sweep frequency of 19–21 kHz in the carbon steel pipe, and (h) sweep frequency of 19–21 kHz in the PVC pipe.

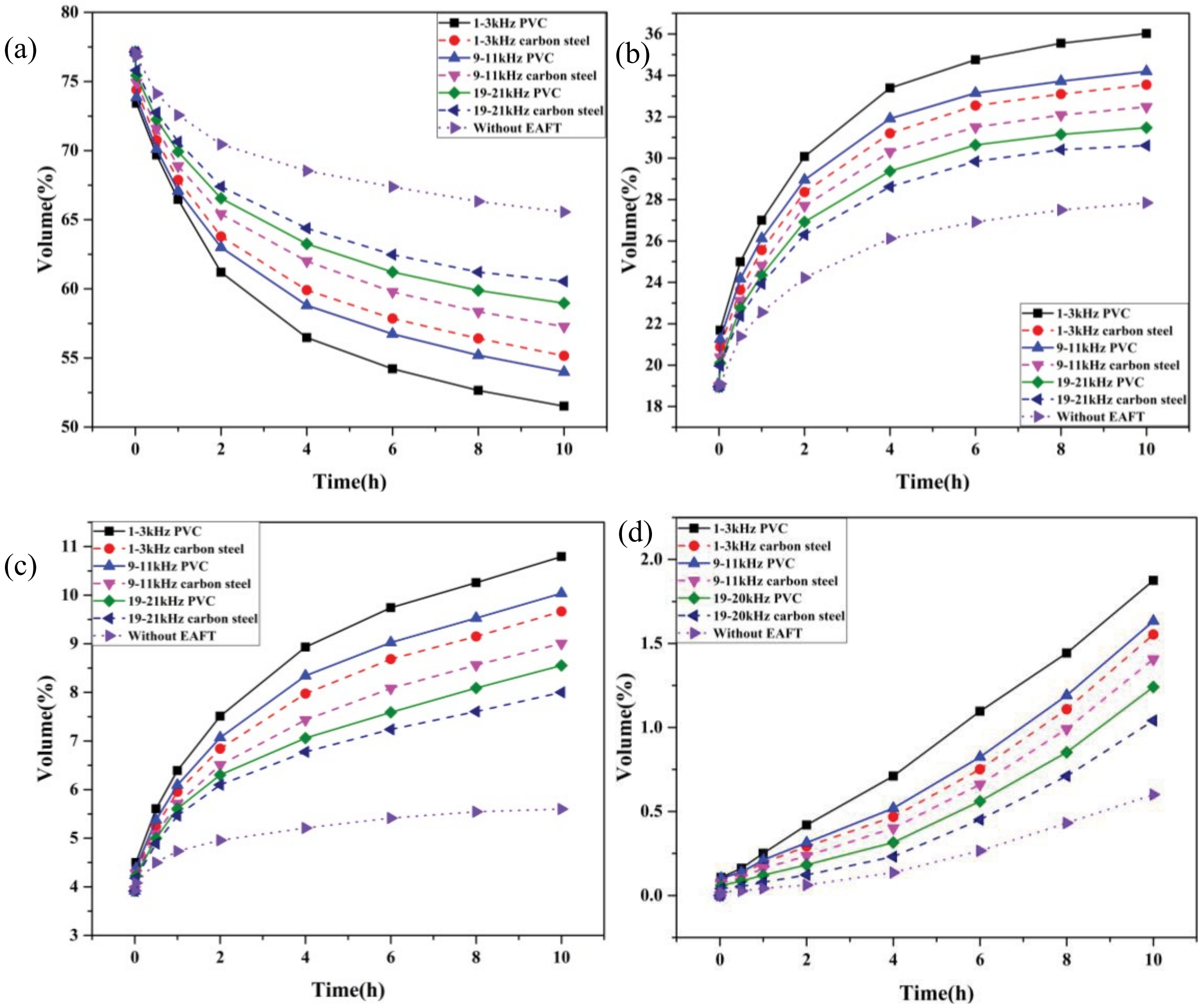

Fig. 8. (a–d) Particle diameter as a percentage of the total particle diameter volume in solution. (a) 0–10 μm, (b) 10–20 μm, (c) 20–30 μm, and (d) 30–40 μm.

- The EAFT system has a helpful anti-fouling effect. It expressed that with EAFT the conductivity and pH declined faster and greater than those without EAFT, with EAFT the average particle diameter increased faster and bigger than that without EAFT, and the particle diameter is significantly increased after EAFT treatment.
- The material of the pipe has a significant impact on the EAF effect. The PVC pipe is better than the carbon steel pipe, it expressed that the solution conductivity and pH in the PVC pipe are smaller than those in the carbon steel pipe, the average particle diameter in the PVC pipe is bigger than that in the carbon steel pipe in the same conditions.
- Under three group sweep frequencies in this experiment, the conductivity decreases with time, the pH rapidly decreases in the first 2 h, then rises slightly, and the average particle diameter increases with time. With the frequency 1–3 kHz, the conductivity and pH declined faster and greater than the others, the average particle diameter is bigger than the others, inducting that the sweep frequency 1–3 kHz has the best anti-fouling effect.

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