

Influence of an Alternating Electric Field on the Coagulation Process and Purifying Effect of FeCl₃ Coagulant

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Received: 11 March 2019 / Accepted: 3 May 2019 / Published: 30 June 2019

In the present study, an experimental study was performed to investigate the influence on the coagulation process and purifying effect of FeCl₃ coagulant in river water caused by electric treatment. The variation in water quality parameters under an electric field with different intensities and frequencies was examined in terms of the solution turbidity, particle size distribution, total organic carbon (TOC), chemical oxygen demand (COD) and zeta potential, and then the mechanism of these variations was discussed. The results showed that after the AEF coagulation treatment, the values of turbidity, COD, TOC and zeta potential decreased. The number of larger suspended particles increased. An electric field with a higher intensity or frequency could obtain a better effect on the removal of pollutants. In addition, the main mechanism of the improvement of removal efficiency was due to the electric field force caused by alternating electric fields, which could enhance the collision between charged particles.

Keywords: Alternating electric field, Coagulation, FeCl₃ coagulant, Zeta potential, Water quality parameters

1. INTRODUCTION

Coagulation is an effective method that can be used to purify or remediate natural water. Aluminium salt and ferric salt are two kinds of widely used coagulants. Aluminium salt has a certain biological toxicity, which is verified to have a correlation with many neurogenic diseases, such as Alzheimer's disease [1,2]. Thus, the use of aluminium salt coagulant may lead to an elevated aluminium level in the water, causing secondary water pollution. By contrast, the ferric salt coagulant has the advantages of no biological toxicity, a higher coagulation and settlement rate, better dewatering of sludge and a shorter water treatment time [3]. However, ferric salt coagulants still have many

disadvantages in practical applications, such as large dosages and high cost. To improve the efficiency of the ferric salt coagulant, some other chemicals are added, such as some kind of surfactant [4]. However, the addition of extra chemicals may import new pollutants. In recent years, some physical methods have been used to improve chemical processes, such as electric fields, magnetic fields, ultrasonics, and ultraviolet rays [5-10]. Alternating electric fields (AEFs) have been used in many water treatment processes. When an electric field is present, every charged particle or phase interface in the water solution is impacted. When the ferric salt coagulant enters the water, the Fe^{3+} quickly combines with the water molecules to form $\text{Fe}(\text{H}_2\text{O})_6^{3+}$, and the $\text{Fe}(\text{H}_2\text{O})_6^{3+}$ shows a strong tendency to hydrolyse in water and form various charged hydroxyl iron ions [11-15]. When an alternating electric field is present, the charged hydroxyl iron ions are influenced. However, thus far, no such study can be found in the literature.

Therefore, in the present study, FeCl_3 coagulant was used to purify actual river water under an AEF treatment, and the purifying effect was investigated by measuring the variation of water quality parameters, including the solution turbidity, particle size distribution, total organic carbon (TOC), chemical oxygen demand (COD) and zeta potential, and the mechanism of these variations was discussed.

2. EXPERIMENT

2.1 Sample Preparation and Experimental setup

In the present study, analytically pure FeCl_3 was used as a coagulant. The water treated in this study was obtained from the Tanghe River, which cuts through Hebei Province in China. The present experiment was carried out during December 2018 since the Tanghe River was in a dry season and the temperature and turbidity of river water were low. The water quality parameters are shown in **Table 1**.

Table 1. Basic water quality parameters of Tanghe River water

pH	Temperature (°C)	Turbidity (NTU)	DOC ($\text{mg}\cdot\text{L}^{-1}$)	Hardness ($\text{mmol}\cdot\text{L}^{-1}$)	Alkalinity ($\text{mmol}\cdot\text{L}^{-1}$)	TOC ($\text{mg}\cdot\text{L}^{-1}$)
7.56	10	13.6	50.79	1.4	1.1	15.35

The experiments were carried out using the setup shown in **Fig. 1**. A cylindrical glass tank with 300 ml experimental solution was positioned in the middle by two electrode pads. The electrode pads were connected to an AEF generator. The generator's output was an alternating signal with a virtual current of 3 A. The stirrer was speed adjustable and was used for stirring in the glass tank. A settling tank was used to store the mixture of water and coagulant after stirring. The temperature of the experimental solution was controlled at 10°C by a thermostatic water bath.

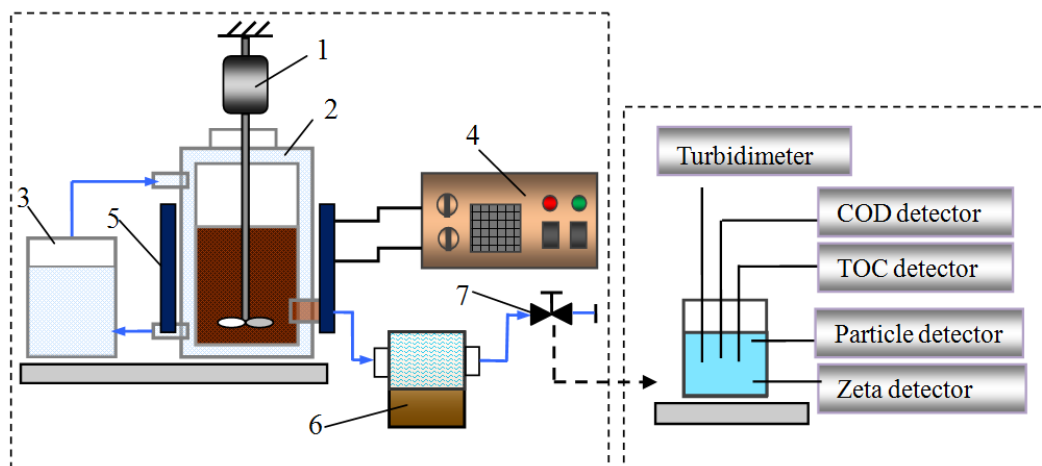


Figure 1. Schematic diagram of the experimental setup. 1-blender, 2-water storage tank, 3-thermostatic water bath, 4-AEF generator, 5-electrode pad, 6-sedimentation tank, 7-sampling point

2.2 Experimental Methods

To investigate the influence of the FeCl_3 coagulation effect on the purification of river water, the experiments were carried out as two parts.

Part 1: the purification efficiency of FeCl_3 coagulation under AEF treatment was investigated by measuring the variations of solution turbidity, particle size distribution, TOC and chemical oxygen demand (COD). Each experiment was conducted for 1 hour. In the first half hour, FeCl_3 powder (10 mg) was added to the river water (500 ml), and NaOH solution was used to adjust the solution pH to 8.5 [16]. The stirring rate was set as 160 rpm, and the mixing time was 15 min. When the floccule took initial shape, the stirring rate was decreased to 40 rpm, and the mixing time was 15 min. In the next half hour, the stirrer was turned off, and the mixed solution was allowed to stand for settlement for 30 min. AEF treatment was performed throughout the entire hour. After the 1 hour experiment, the supernatant liquid was sampled for the measurement of turbidity, particle size distribution, TOC and COD. Then, the above experiment and measurement process was repeated with different magnetic field exciting currents.

Part 2: the influence on the surface charge performance of floccules caused by AEF-coagulation treatment was investigated by measuring the zeta potential of suspended particles in the mixing solution. Each experiment was conducted for 15 min. FeCl_3 powder (10 mg) was added to the river water (500 ml), and NaOH solution was used to adjust the solution pH to 8.5. The stirring rate was set as 160 rpm, and the mixing time was 15 min. When the floccule took initial shape, the mixing solution was sampled for the measurement of zeta potential. The AEF treatment was performed throughout the whole 15 min. Then, the above experiment and measurement process was repeated with different magnetic field exciting currents (a larger exciting current causes a higher magnetic field intensity).

In addition, the same experiment without AEF treatment was also performed for comparison. All the parameters were measured 3 times, and the average values were calculated to reduce

measurement errors. The information of the experimental instrument used in the present study is shown in **Table 2**.

Table 2. Experimental instrument information

Experimental instrument	Model	Manufacturer
Turbidimeter	WJS-186	Shanghai INESA Scientific Instrument Co., Ltd
Particle detector	JWG-8A	TIAN JIN KangHuiHungMei Technology Co., Ltd
COD detector	COD-4210	Shimadzu Corporation
TOC detector	TOC-V CPH	Shimadzu Corporation
Zeta potential detector	JS94H	Shanghai ZhongChen Scientific Instrument Co., Ltd

3. RESULTS AND DISCUSSION

3.1 Influence of the AEF treatment on the solution turbidity

In the present study, the particle size distribution in the solution after AEF coagulation treatment was investigated. After the settling procedure, the supernatant of the solution was obtained, and the numbers of particles with sizes of 2~5 μm , 5~8 μm , 8~10 μm , 10~12 μm , 12~25 μm and 25~100 μm were measured. The variation of the particle size distribution is shown in **Fig. 2**.

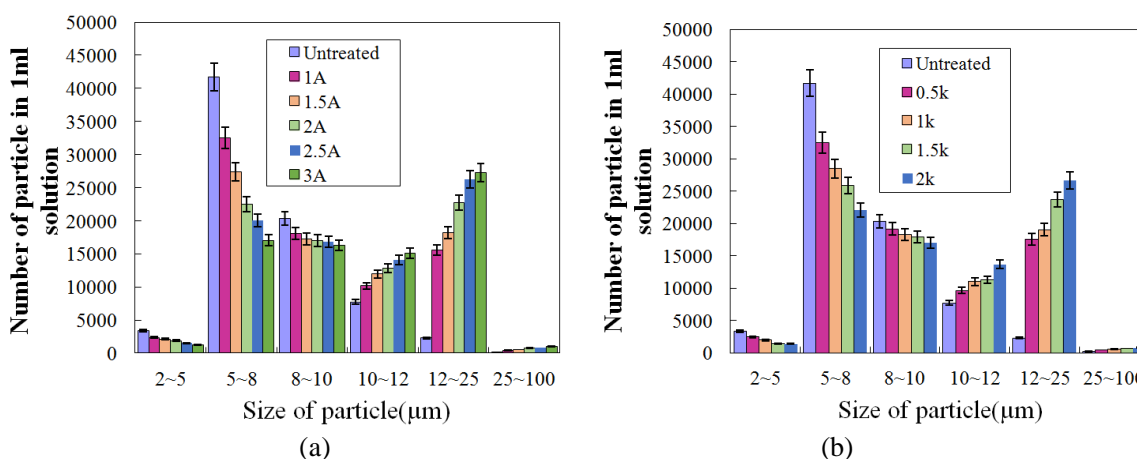


Figure 2. The variation of the particle size distribution under the AEF-coagulation treatment. (a) Under electric fields with different intensities and (b) under electric fields with different frequencies.

As shown in **Fig. 2(a)** and **Fig. 2(b)**, it can be seen that following treatment by an alternating electric field, the turbidity values are all observably lower than those under no electric field. This result indicates that an alternating electric field can enhance the FeCl_3 coagulant's ability to remove turbidity. The intensity and frequency of the electric field are important parameters that may influence the turbidity removal efficiency. According to **Fig. 2(a)**, it can be observed that the turbidity values are

3.50 NTU, 3.44 NTU, 3.18 NTU, 3.02 NTU and 2.89 NTU when the exciting currents are 1 A, 1.5 A, 2 A, 2.5 A and 3 A, respectively, which indicates that the turbidity value decreases with increasing electric field intensity. According to **Fig. 2 (b)**, it can be seen that the turbidity values are 3.57 NTU, 3.38 NTU, 3.29 NTU and 3.11 NTU when the exciting frequencies are 0.5 kHz, 1 kHz, 1.5 kHz and 2 kHz, respectively, which indicates that the turbidity value decreases with increasing electric field frequency. Therefore, the results in **Fig. 2** indicate that a higher intensity and frequency of the electric field can obtain a better effect on turbidity removal by FeCl_3 coagulant.

As shown in **Fig. 2**, it can be seen that the distribution range of the size of most particles is 5~25 μm . In the present study, the particles were considered small when the size distribution range was 5~10 μm , and correspondingly, the particles were considered large when the size distribution range was 10~25 μm . According to **Fig. 2**, it can be observed clearly that there are more small particles in the untreated supernatant but more large particles in the AEF-treated supernatant. This result indicates that an alternating electric field can promote the formation of larger particles and hinder the formation of smaller particles. As shown in **Fig. 2(a)**, the intensity of the electric field has an impact on the particle size. The number of large particle sizes increases proportionally to the field intensity. Analogously, as shown in **Fig. 2(b)**, the number of large particle sizes increases proportionally to the field frequency. Therefore, it can be concluded that a higher intensity and frequency of the electric field can obtain more large particles but fewer small ones.

In the present study, FeCl_3 coagulant was used to remove the organic pollutants in river water. When FeCl_3 is added to the water, Fe^{3+} can unite with the functional group (such as $-\text{COON}$, $-\text{OH}$) of macromolecular substances and form into larger complex particles. In addition, some Fe^{3+} ions are quickly combined with the water molecules to form $\text{Fe}(\text{H}_2\text{O})_6^{3+}$. $\text{Fe}(\text{H}_2\text{O})_6^{3+}$ shows a strong tendency to hydrolyse in water and form various hydroxyl iron ions, such as FeOH^{2+} , $\text{Fe}(\text{OH})^{2+}$, $\text{Fe}_2(\text{OH})_2^{4+}$ and $\text{Fe}_3(\text{OH})_4^{5+}$ [11, 12]. Then, under the effect of polyreaction, these oligomers tend to accumulate and form into high polymers, which can also capture organic pollutants by net catching and sweeping. Then, all of the larger complex particles and high polymers with organic pollutants cluster and precipitate. When the electric field is present, the hydrolysis reaction of the metal cation can be promoted [16]. In the present study, a similar result was obtained. According to the results in **Fig. 2**, it can be concluded that an electric field can promote the hydrolysis reaction of $\text{Fe}(\text{H}_2\text{O})_6^{3+}$ and further enhance the formation of high polymers with large sizes; thus, the number of small particles is decreased.

3.2 Influence of AEF treatment on the particle size distribution

The removal of turbidity is an important process of drinking water treatment. The turbidity is caused by the suspended particles in the water, which can be removed by coagulation. In this section, the influence of AEF treatment on the process of coagulation-removing turbidity is investigated. The variation of turbidity under the AEF-coagulation treatment is shown in **Fig. 3**.

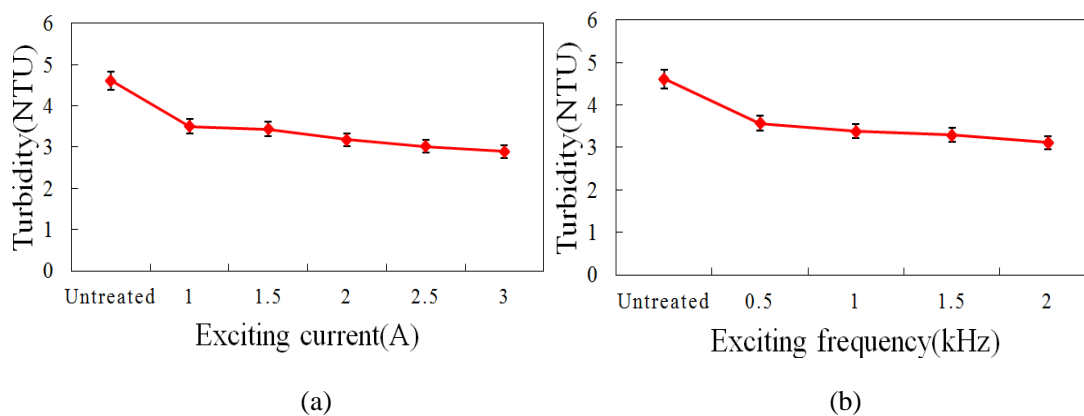


Figure 3. The variation of turbidity under the AEF-coagulation treatment. (a) Under electric fields with different intensities and (b) under electric fields with different frequencies.

As shown in **Fig. 3 (a)** and **Fig. 3 (b)**, it can be seen that when treated by an alternating electric field, the turbidity values are all observably lower than those under no electric field. This result indicates that an alternating electric field can enhance the FeCl_3 coagulant's ability to remove turbidity. The intensity and frequency of the electric field are important parameters that may influence the turbidity removal efficiency. According to **Fig. 3 (a)**, it can be observed that the turbidity values are 3.50 NTU, 3.44 NTU, 3.18 NTU, 3.02 NTU and 2.89 NTU when the currents are 1 A, 1.5 A, 2 A, 2.5 A and 3 A, respectively, which indicates that the turbidity value decreases with increasing electric field intensity. According to **Fig. 3 (b)**, it can be seen that the turbidity values are 3.57 NTU, 3.38 NTU, 3.29 NTU and 3.11 NTU when the frequencies are 0.5 kHz, 1 kHz, 1.5 kHz and 2 kHz, respectively, which indicates that the turbidity value decreases with increasing electric field frequency. Therefore, the results in **Fig. 3** indicate that a higher intensity and frequency of the electric field can obtain a better effect on turbidity removal by FeCl_3 coagulant.

As is well known, the solution turbidity depends on the number and size of suspended particles. A larger number of suspended particles can promote a higher turbidity. Suspended particles with a small size can also result in high turbidity since the small particle can suspend in the solution more easily. The lower turbidity obtained after the AEF treatment means that the electric field reduces the number of suspended particles or hinders the formation of small particles, and this deduction can be proved by the results in **Fig. 2** above. One reason for these results may be that the electric field increases the viscosity of the solution. Zhu L's [17] study showed that an electric field can effectively increase the viscosity of inorganic salt solutions. According to Stokes' law, the increase in the viscosity of the solution can slow the sedimentation rate of various hydroxyl iron ions and prolong the lifetime of the intermediate hydroxyl iron polyreaction, which can enhance the charge neutralization ability of hydrolysate. Then, more colloidal particles are destabilized and gather as larger particles.

3.3 Influence of the AEF treatment on the removal of COD and TOC

The values of COD and TOC are always measured to reveal the amount of organic pollutants in river water. In the present study, the COD and TOC values of the supernatant after AEF coagulation treatment were measured, and the results are shown in **Fig. 4**.

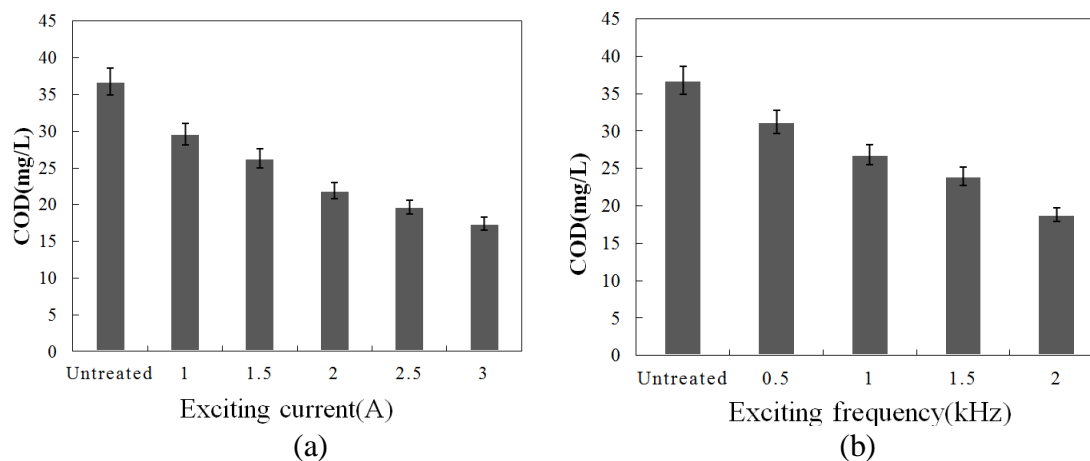


Figure 4. The variation of the value of COD under the AEF-coagulation treatment. (a) Under electric fields with different intensities and (b) under electric fields with different frequencies.

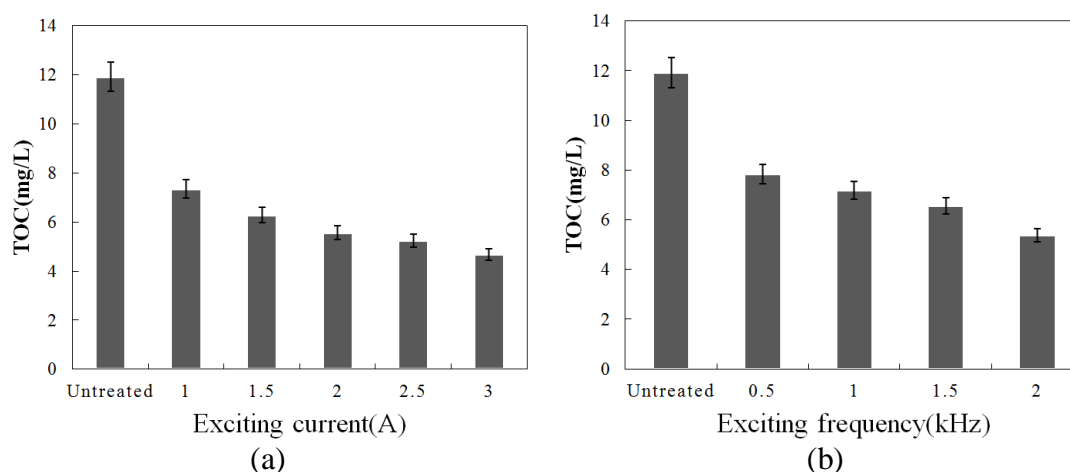


Figure 5. The variation of the value of TOC under the AEF-coagulation treatment. (a) Under electric fields with different intensities and (b) under electric fields with different frequencies.

As shown in **Fig. 4**, compared with the COD value ($36.79 \text{ mg}\cdot\text{L}^{-1}$) under no electric field, the COD values under the AEF treatment are lower. This result indicates that the AEF treatment enhances the efficiency of COD removal, which means that more pollutants in the river water are removed by the AEF coagulation treatment process. The COD concentration values of the supernatant treated by the electric field with different intensities are shown in **Fig. 4(a)**. As seen from **Fig. 4(a)**, the COD concentration values are $29.61 \text{ mg}\cdot\text{L}^{-1}$, $26.32 \text{ mg}\cdot\text{L}^{-1}$, $21.88 \text{ mg}\cdot\text{L}^{-1}$, $19.67 \text{ mg}\cdot\text{L}^{-1}$ and $17.40 \text{ mg}\cdot\text{L}^{-1}$ when the exciting currents are 1 A, 1.5 A, 2 A, 2.5 A and 3 A, respectively. This result indicates that the COD concentration decreases with increasing field intensity. **Fig. 4(b)** shows the COD concentration values of the supernatant treated with electric field at different frequencies. The COD concentration values are $31.25 \text{ mg}\cdot\text{L}^{-1}$, $26.88 \text{ mg}\cdot\text{L}^{-1}$, $23.97 \text{ mg}\cdot\text{L}^{-1}$ and $18.84 \text{ mg}\cdot\text{L}^{-1}$ when the exciting frequencies are 0.5 kHz, 1 kHz, 1.5 kHz and 2 kHz, respectively, which means that the COD concentration decreases with increasing field frequency. All the results in **Fig. 4** show that an electric field with higher intensity or frequency is beneficial for the coagulation removal of COD in river water.

It can be seen from **Fig. 5** that there is a similar variation trend between the TOC values and electric field parameters compared with the COD values in **Fig. 4**. All electric fields applied in this study can induce lower TOC values than those under no electric field ($11.92 \text{ mg}\cdot\text{L}^{-1}$). According to **Fig. 5 (a)**, the TOC values are $7.35 \text{ mg}\cdot\text{L}^{-1}$, $6.28 \text{ mg}\cdot\text{L}^{-1}$, $5.56 \text{ mg}\cdot\text{L}^{-1}$, $5.23 \text{ mg}\cdot\text{L}^{-1}$ and $4.67 \text{ mg}\cdot\text{L}^{-1}$ when the exciting currents are 1 A, 1.5 A, 2 A, 2.5 A and 3 A, respectively. According to **Fig. 5 (b)**, the TOC values are $7.84 \text{ mg}\cdot\text{L}^{-1}$, $7.19 \text{ mg}\cdot\text{L}^{-1}$, $6.57 \text{ mg}\cdot\text{L}^{-1}$ and $5.38 \text{ mg}\cdot\text{L}^{-1}$ when the exciting frequencies are 0.5 kHz, 1 kHz, 1.5 kHz and 2 kHz, respectively. The results show that the TOC concentration decreases with increasing field intensity and frequency. Thus, it can be concluded that a higher intensity and frequency of electric field can ensure better TOC removal efficiency.

The major organic pollutants in natural water are natural organic matter (NOM). It is acknowledged that NOM contains many kinds of complex aromatic polymers that have many functional groups (such as carboxyl, hydroxy, phenolic hydroxy, and carbonyl) [18]. Most NOM exists as anions in natural water. It can interact with other ions or molecules and form into macromolecular substances, which can adsorb on the surface of suspended particles. When Fe^{3+} ions hydrolyse in water and form various hydroxyl iron ions, the macromolecular substance is adsorbed by the polymer of hydroxyl iron. According to the results in **Fig. 2**, the electric field promotes the formation of larger particles but reduces the number of small particles, which means that the sum of the specific surface area is decreased; this change inhibits the adsorption of NOM. However, as shown in **Fig. 4** and **Fig. 5**, the values of COD and TOC decreased when the electric field was added, which means that the adsorption of NOM by the polymer of hydroxyl iron was enhanced. In the present study, the pH value was 8.5 during the treatment process. Under this pH value, $\text{Fe}(\text{H}_2\text{O})_6^{3+}$ shows a strong tendency to hydrolyse in water and form high polymers [16], which further form floccules. This floccule can remove organic pollutants by net catching and sweeping. According to the results in **Fig. 2**, **Fig. 4** and **Fig. 5**, the electric field promotes the formation of floccules with larger sizes, thus enhancing the performance of net catching and sweeping.

3.4 Influence of the AEF treatment on the Zeta potential

The zeta potential can be measured to characterize the stability of the colloid particles formed by FeCl_3 coagulant. In a water system with suspension colloids, a relatively high zeta potential may imply a high colloid stability. Conversely, a low zeta potential may mean that the colloid particles have a trend of aggregation. In the present study, the zeta potential of the mixed solution after a 15 min AEF-coagulation treatment was measured, and the results are shown in **Fig. 6**.

As shown in **Fig. 6**, it can be seen that under the AEF treatment, the values of zeta potential are all observably lower than those under no field (-4.56 mV). This phenomenon indicates that the AEF treatment can decrease the surface charge of the floccule formed by FeCl_3 coagulant. The zeta potential values under AEF treatment with different intensities are shown in **Fig. 6 (a)**. As seen from **Fig. 4 (a)**, the zeta potential values are -2.22 mV , -1.96 mV , -1.75 mV , -1.39 mV and -0.85 mV when the exciting currents are 1 A, 1.5 A, 2 A, 2.5 A and 3 A, respectively. **Fig. 6 (b)** shows the zeta potential values under AEF treatment with different frequencies. The zeta potential values are -2.31 mV , -1.98 mV , -

1.62 mV and -1.10 mV when the exciting frequencies are 0.5 kHz, 1 kHz, 1.5 kHz and 2 kHz, respectively. Therefore, the results in Fig. 6 indicate that an electric field with higher intensity or frequency can reduce the surface charge of the floccule more effectively.

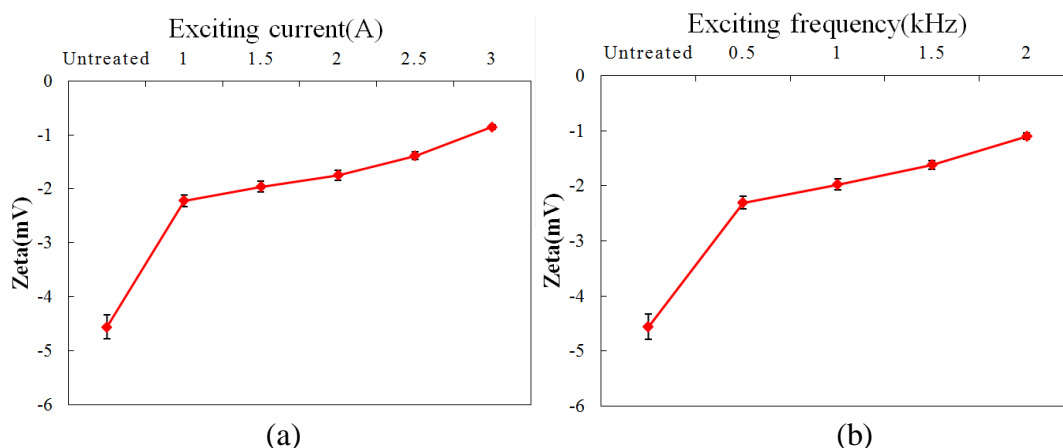


Figure 6. The variation of the value of the zeta potential under the AEF-coagulation treatment. (a) Under electric fields with different intensities and (b) under electric fields with different frequencies.

The zeta potential is a measure of the strength of the repulsion or attraction between particles. It is acknowledged that particles with smaller size have a higher zeta potential, which can make the suspension liquid system more stable. Inversely, particles with larger size have a lower zeta potential, which can make the suspension liquid system unstable. According to the results in Fig. 3 and Fig. 6, the larger particles made by AEF treatment indeed lead to a lower zeta potential. In addition, the average charge per unit of iron may be increased by the AEF treatment, providing FeCl₃ coagulant with a stronger ability to maintain charge neutrality; thus, the destabilization of suspended particles is enhanced, and more large particles can be formed and precipitate.

3.5 Discussion on the mechanism of enhanced FeCl₃ coagulation by AEF

During the coagulation process described above, the collision between particles is essential. Since the electric field can shift the charged particles by the electric field force, when the electric field is applied, the kinetic energy of particles is increased, and the collision between particles is enhanced. The enhanced collision promotes the formation of larger particles that can precipitate more easily, and then more organic pollutants can be removed from water. According to the results in Fig. 2, since the collision was enhanced by AEF treatment, larger particles were formed. Then, more organic pollutants were removed by precipitation, which produced a lower turbidity (see the results in Fig. 3). The results in Fig. 4 and Fig. 5 can also be presented as evidence since the reduction in organic pollutants can lead to a lower concentration of COD and TOC. The increased particle size can change the zeta potential of the mixing solution.

The electric field intensity is an important parameter that directly influences the magnitude of the electric field force. The electric field force can be calculated as [18]:

$$F = qE \quad (1)$$

where q is the particulate charge and E is electric field intensity. In the present study, the electric field intensity was determined by the current value. When the electric field intensity increases, the electric field force increases accordingly, which leads to an increase in particle kinetic energy, and thus, collision among the particles is enhanced. This conclusion can be proven by the experimental results presented in the previous sections. In addition, an increase in frequency can enhance the collision between particles. [19,20,21] The alternating electric field applied in the present study applied a direction-dependent electric field force on the charged particles. The frequency of this direction change is in accordance with the applied frequency. In every period, the direction of the electric field force in the first half period is opposite the direction of the electric field force in the second half period. This direction change of the electric field force on the particles is a kind of disturbance that can also increase the probability of collision between particles. Therefore, a higher frequency may cause a higher probability of collision. This conclusion is also supported by the experimental results in the previous sections.

The promotion of the hydrolysis reaction of FeCl_3 in water caused by alternating electric fields may be another reason for the performance improvement of FeCl_3 coagulant. Some previous study results [22, 23] showed that alternating electric fields can facilitate the hydrolysis reaction of some soluble metal inorganic salts. In the present study, the hydrolysis reaction of FeCl_3 was possibly promoted by an electric field, which caused more hydroxyl iron ions to form. Thus, more flocs were formed, which could remove more pollutants by net catching and sweeping.

4. CONCLUSION

In the present article, the removal efficiency of pollutants in river water using FeCl_3 coagulant under AEF treatment was investigated. After the AEF coagulation treatment, the water quality parameters were measured, and the results were discussed. Some important conclusions were obtained as follows:

- (1) When FeCl_3 was used as a coagulant, after the AEF coagulation treatment, the values of turbidity, COD, TOC and zeta potential decreased observably. Many larger suspended particles were formed in the water, and inversely, the number of small suspended particles decreased.
- (2) An electric field with a relatively high intensity or frequency is beneficial for the removal of pollutants in river water.
- (3) The enhanced collision between particles caused by the electric field force was concluded to be the main mechanism of the improvement of removal efficiency. In addition, the promotion of the hydrolysis reaction of FeCl_3 in water caused by alternating electric fields may be another reason for the performance improvement of FeCl_3 coagulant.

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