Combined treatment of organic material in oilfield fracturing wastewater by coagulation and UV/H2O2/ferrioxalate complexes process

Dan Ge

ABSTRACT

Organic material is considered to be a main component of oilfield fracturing wastewater (OFW). This work is intended to optimize the experimental conditions for the maximum oxidative degradation of organic material by coagulation and the UV/H2O2/ferrioxalate complexes process. Optimal reaction conditions are proposed based on the chemical oxygen demand (COD) removal efficiency. The overall removal efficiency of COD reached 83.8% when the dilution ratio of raw wastewater was 1:2, the pH was 4 and the FeCl₃ loading was 1,000 mg/L in the coagulation process; the dosage of H₂O₂ (30%, v/v) was 0.6% (v/v) and added in three steps, the n(H₂O₂)/n(Fe²⁺) was 2:1, n(Fe²⁺)/n(C₂O₄²⁻/C₀) was 3:1 and the pH was 4 in the UV/H₂O₂/ferrioxalate complexes process; the pH was adjusted to 8.5-9 with NaOH and then 2 mg/L of cationic polyacrylamide (CPAM) was added in the neutralization and flocculation process. The decrease in COD during the coagulation process reduced the required H₂O₂ dosage and improve efficiency in the subsequent UV/H₂O₂/ferrioxalate complexes process. Furthermore, there was a significant increase of 13.4% in the COD removal efficiency with the introduction of oxalate compared with UV/Fenton. Experimental results show that the coagulation and UV/H₂O₂/ferrioxalate complexes process could efficiently remove the organic material dissolved in OFW. An optimal combination of these parameters produced treated wastewater that met the GB8978-1996 ‘Integrated Wastewater Discharge Standard’ level III emission standard.

Key words | coagulation process, oilfield fracturing wastewater, organic material, UV/H₂O₂/ferrioxalate complexes process

INTRODUCTION

Organic material is widely used in the hydraulic fracturing process. In the oilfield production process, large amounts of residual guar gum wastewater are generated (Nevin et al. 2017; Britt 2017; Hickenbottom et al. 2015). This oilfield fracturing wastewater (OFW) also contains various organics pollutants, impurities, solids, heavy metals, polymers, chemical additives, proppants, oil, etc (Chen et al. 2011; Jian 2017; Stringfellow et al. 2014), significantly increasing the chemical oxygen demand (COD), chrominance and salinity, viscosity and strong acidity. Up to 15,140,000 litres of water-based fluid could be injected into a single drilled well to both initiate and expand fractures during hydraulic fracturing, and act as proppant transport, of which 10–70% is subsequently recovered as flowback (Lester et al. 2015). This OFW contains high concentrations of potential organic pollutants and inorganic constituents, and it requires some degree of treatment. However, hydraulic fracturing in underground gas and oil operations produces contaminated wastewater that is difficult to treat (Chapman et al. 2011; Vengosh et al. 2013). Furthermore, OFW has become one of the main sources of water pollution in oilfields and can considerably increase environmental hazards if discharged without effective treatment (Olsson et al. 2013). With the improvement of environmental protection standards and the need to save energy and reduce emissions, an advanced treatment for OFW is necessary to satisfy the wastewater discharge quality or to reuse wastewater (Mehta & O’Sullivan 2015).

Currently, the treatment methods for OFW include the advanced oxidation process, chemical coagulation,
electrocoagulation, biological methods, activated carbon adsorption and solidification methods (Bagal & Gogate 2014; Akyon et al. 2015; Esmaeilrad et al. 2015; Benincá et al. 2016; Rosenbluma et al. 2016), all of which have various shortcomings. For example, some methods require high processing costs, complex processing equipment, or a large amount of oxidizing agents (Rahm et al. 2013), while other methods can produce additional pollutants that do not meet national wastewater discharge standards (Hladik et al. 2014). Treatment processes that address all types of wastewater have not yet been developed and they must be refined and improved to increase the efficiency and reduce the economic costs of hydraulic fracturing.

The UV/H2O2/ferrioxalate complexes method is an emerging and promising oxidation process based on Fenton to treat high concentrations of toxic and hazardous biological materials in refractory wastewater. It is a chemical process that removes contaminants in the liquid phase, and it usually requires UV radiation and an agent to oxidize organic pollutants to CO2, water, and inorganic or small organic molecules. It not only has a strong ability to make full use of ultraviolet and visible light, but the hydroxyl radical (-OH) production rate is high for oxidative degradation of organic matter (Nogueira et al. 2000; Salem et al. 2009; Bing et al. 2015). Compared to the ferrous sulphate salt, ferrioxalate has high light activity, which is beneficial for hydroxyl radical production. The reaction of ferric ions with C2O4\(^2-\) generates Fe(C2O4)\(^3-\) and ferrioxalate complexes under UV irradiation, which have great potential photocatalytic activity. Fe(C2O4)\(^3-\) has a high molar absorption coefficient at wavelengths higher than 200 nm and even absorb 500 nm visible light to generate Fe2+. The photolysis mechanism of Fe(C2O4)\(^3-\) is as follows (Ali et al. 1994; Xie et al. 2000; Lehóczki et al. 2018; Augustina et al. 2015):

\[
\text{Fe(C2O4)\(^3-\)} + \text{hv} \rightarrow \text{Fe}^2+ + 2\text{C2O4}\(^2-\) + \text{CO}_2 \cdot + \text{CO}_2.
\]

(1)

\[
\text{C2O4}\cdot + \text{Fe}^2+ \rightarrow \text{Fe(C2O4)\(^3-\)} + \text{CO}_2 + 2\text{CO}_2 \cdot + \text{CO}_2.
\]

(2)

\[
\text{C2O4}\cdot + \text{CO}_2 \rightarrow \text{CO}_2 \cdot + \text{CO}_2.
\]

(3)

In an an aqueous solution, C2O4\cdot and CO2\cdot will further react with O2 and generates H2O2 in acidic conditions.

\[
\text{C2O4}\cdot + \text{CO}_2 \cdot + \text{O}_2 \rightarrow \text{O}_2 \cdot + 2\text{CO}_2/\text{CO}_2.
\]

(4)

\[
2\text{O}_2 \cdot + 2\text{H}^+ \rightarrow \text{H}_2\text{O}_2 + \text{O}_2.
\]

(5)

Thus, it uses less reagents than the traditional Fenton reaction under light photolysis of ferrioxalate complexes into Fe2+ and H2O2. In addition, the dose of H2O2 also decreases with the added C2O4\(^2-\) (Ali et al. 1994; Zhang et al. 2002). The UV/H2O2/ferrioxalate complexes process is not only less damaging to the environment but is also more economical compared with other advanced oxidation processes. Compared with traditional treatments, the method is advantageous because it has a wide range of applications, higher efficiency, produces little secondary pollution and the chemical reaction is completed during the treatment process (Yan et al. 2014).

As the aim of this work was to further improve the efficiency of wastewater treatment, the process of coagulation was used to pretreat the OFW for the removal/separation of organic/inorganic or suspended/soluble colloids in water/solution (Verma et al. 2010). Then, the effectiveness of UV/H2O2/ferrioxalate complexes process in treating OFW was explored. Experiments were conducted to explore the effects of various operating conditions using a laboratory-scale reactor. The merits of the photochemical method employed for the pretreatment of wastewater were primarily due to the method’s simplicity, high removal efficiency and easy onsite implementation.

MATERIALS AND METHODS

Laboratory instruments and chemicals

An ultraviolet spectrophotometer (UV-8000, Metash Instruments Co., Ltd, China) and quartz cuvettes were used for measurements of absorbance analysis and COD using a dichromate solution as the oxidant in strong acid media. pH values were determined by using an acidometer (PHS-3C, INESA Scientific Instrument Co., Ltd, China). Oxidation experiments were conducted with a six-joint heat-collection temperature magnetic stirrer (HJ-6, Changzhou ZOJE Experimental Instruction Manufacturing Co., Ltd, China). Ultraviolet was generated using a UV lamp (300 W, Shanghai Metash Instruments Co., Ltd, China). A vacuum filtration device (FS3310, Shanghai Metash Instruments Co., Ltd, China) was also needed for treating the effluent.

The hydrogen peroxide (H2O2, 30%, w/w), sodium hydroxide (NaOH), hydrochloric acid (HCl), ferrous sulfate heptahydrate (FeSO4·7H2O), oxalic acid (H2C2O4), cationic polyacrylamide (CPAM), potassium dichromate (K2Cr2O7)
were of analytical grade, and other chemicals used were analytical reagent (AR) grade. All solutions were prepared with distilled water.

Raw fracturing wastewater employed in this study was obtained from five different operating areas of CNOOC (China National Offshore Oil Corporation) in Tianjin province, China. The oil was skimmed before use. The wastewater was stored at 4°C until required. The main characteristics of sample wastewater are listed in Table 1. The value is the average value of five samples. As shown, the oilfield wastewater had high concentrations of COD, total dissolved solids and suspended solids (SS). Moreover, the oilfield wastewater had high color.

### Experimental setup

The experimental setup is shown in Figure 1. The coagulation and UV/H2O2/ferrioxalate complexes reactor designed was used batch-wise in all experiments and was a 400 mm × 500 mm × 1,500 mm cube with a working volume of 250 L. Pharmaceuticals were added to the reactor according to need, and circulating cooling water was used to keep the reaction system at 25°C. A 300 W Hg lamp in a quartz sleeve was placed in the middle of the reactor. After completion of the reaction, NaOH solution was added to adjust the pH to 8.5–9. After precipitation, the supernatant was tested for each parameter.

### Coagulation experiments

The coagulation process was carried out with 1 L wastewater samples at 25 °C in a jar-tester apparatus. The following conditions were evaluated: pH, mixing time and coagulant dosages. A large number of laboratory experiments found that ferric chloride is better than ferric sulphate as a coagulant, and ferric chloride is much cheaper, so the coagulant evaluated in this study was FeCl3 (analytical grade). To determine the effective coagulant dose for the OFW treatment, a batch jar test apparatus equipped with six glass beakers (1 L) was used to conduct the coagulation experiments. A coagulant dosage in the range of 400–1,200 mg/L under the optimum pH condition was studied. Before the UV/H2O2/ferrioxalate complexes experiments, I conducted several early experiments on the coagulant dosage and found a coagulant dosage in the range of 400–1,200 mg/L under the optimum pH condition better than others.

Immediately after adding the coagulant, the samples were rapidly mixed for 5 min at 150 rpm, followed by a slow mixing stage for 20 min at 15 rpm and subsequent settling of the sludge sediment for 30 min. After the settling period, the supernatant was withdrawn from the beakers and used for analysis. Meanwhile, the pH value of the samples was adjusted to the desired levels by addition of appropriate amounts of H2SO4 (5%, v/v) or NaOH (5%, w/v).

### Table 1 | Characteristics of the raw oilfield wastewater

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>/</td>
<td>6.5</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>4,069–4,386</td>
</tr>
<tr>
<td>BOD5</td>
<td>mg/L</td>
<td>776</td>
</tr>
<tr>
<td>Suspended solids (SS)</td>
<td>mg/L</td>
<td>562–588</td>
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<tr>
<td>Color</td>
<td></td>
<td>165 (turbid and light yellow)</td>
</tr>
<tr>
<td>Organic material</td>
<td>mg/L</td>
<td>3,929–4,276</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg/L</td>
<td>5,126</td>
</tr>
<tr>
<td>Oil and grease</td>
<td>mg/L</td>
<td>37</td>
</tr>
</tbody>
</table>

### Figure 1 | Schematic diagram of the experimental setup. (1) pH adjusting tank; (2) pH meter; (3) Stirrer; (4) Heating/cooling unit; (5) Condensate outlet; (6) Reaction vessel; (7) Stent; (8) Condensate imports; (9) UV irradiation system; (10) Effluent; (11) Sludge precipitation; (12) Peristaltic pump.
Furthermore, in order to study the influence of the addition method (in one, two and three steps) on the removal of COD, the same dosage of coagulant was divided into one, two and three equal volumes, respectively. Then, they were evenly added into different water samples.

**UV/H2O2/ferrioxalate complexes experiments**

The UV/H2O2/ferrioxalate complexes experiments were carried out after coagulation. The oxidative treatment of the OFW was performed at 25 °C and atmospheric pressure. Operating parameters including initial pH, H2O2 dosage, the n(H2O2)/n(Fe2+) and n(Fe2+)/n(C2O42-) were investigated.

The experiments were performed using a laboratory-scale batch reactor composed of 500 mL in a batch cylindrical glass photoreactor, a known volume of H2O2 (30%, v/v) solution, FeSO4.7H2O and H2C2O4 loaded into the reactor under vigorous magnetic stirring and UV irradiation, respectively. The supernatant was withdrawn for COD analysis after allowing the treated wastewater to stand for 30 min.

**Neutralization and flocculation experiments**

After the coagulation/UV/H2O2/ferrioxalate complexes process, NaOH was added to the water to adjust the pH to 8.5–9. Then, adding an appropriate amount of CPAM (0.1% w/v) led to the formation of large precipitates immediately. After standing for 30 min, the water was filtered through 0.45 μm membrane by the vacuum filtration device.

All experiments in this study were performed in triplicate to get reliable data, and the results presented here represent the average values of three independent measurements.

**RESULTS AND DISCUSSION**

**Coagulation process studies**

Using the coagulation process to remove dissolved organic matter, SS and other colloidal solids in wastewater was cost-effective (Pliego et al. 2014). Furthermore, this process could considerably reduce the COD of the wastewater, thereby resulting in a lower H2O2 requirement in the subsequent UV/H2O2/ferrioxalate complexes process. Experiments were carried out to study the dilution ratio, pH and FeCl3 dosage.

**Effect of the dilution ratio**

Usually, it is important from an application point of view to study the dilution ratio of the pollutant, because the dilution ratio is an important factor affecting the process, directly affecting the costs in water treatment and the purification effect. Therefore, the effect of OFW dilution ratio (namely initial COD of the wastewater) on the degradation efficiency was investigated at different dilution ratios (0, 1:1, 1:2, 1:3) and presented in Figure 2(a). It can be observed that the COD removal increased significantly as the dilution ratio increased up to 1:2. When the dilution ratio increased from 1:2 to 1:3, however, the COD removal efficiency only slightly increased from 44.5% to 46.1%. This may be due to the fact that the wastewater had a high

![Figure 2](https://iwaponline.com/wst/article-pdf/77/4/909/493982/wst077040909.pdf)

*Figure 2*  (a) Effect of dilution ratio of OFW on COD removal during coagulation (experimental conditions: FeCl3, 900 mg/L; pH, 4; COD of raw wastewater, 4,320 mg/L). (b) Effect of pH value of OFW on COD removal during coagulation (experimental conditions: FeCl3, 900 mg/L; dilution ratio, 1:2).
organic content, which caused relatively high resistance to coagulation, leading to difficulty in floc formation, and thus leading to slow sedimentation and poor coagulation efficiency under the condition of low dilution ratio. Therefore, the raw OFW should be diluted twice before the coagulation process.

**Effect of pH**

The pH value is an important parameter that affects coagulation efficiency (Wang et al. 2013). Figure 2(b) shows the efficiency of coagulation with FeCl₃ at different pH values. The maximum COD removal (43.6%) was observed at pH 4. COD removal efficiency decreased after increasing or decreasing the pH value from pH 4. The same COD reduction phenomenon was observed when OFW effluent was subjected to the coagulation process. Therefore, the pH value of 4 was selected for the following experiments. FeCl₃ hydrolysis was performed and complex ions, such as Fe(OH)²⁺, Fe₂(OH)₄²⁺, Fe₃(OH)₅⁴⁺ with high positive charge and a low degree of polymerization were formed at low pH; charge neutralization was selected as the main mechanism of the coagulant (Tatsi et al. 2009). FeCl₃ reduces coagulation efficiency by forming free iron ions at extremely low pH levels. The coagulation function will decrease because of the reduction of the degree of FeCl₃ depolymerization when the pH is too high.

**Effect of FeCl₃ dosage**

Figure 3 shows the effect of FeCl₃ dosage on COD removal during coagulation. COD reduction increased with increasing FeCl₃ dosage. According to the adsorption and charge neutralization theory, the negatively charged colloids in wastewater are adsorbed by the positively charged colloids of the dissociation of FeCl₃. Meanwhile, a slow decrease in COD removal was observed when the FeCl₃ dosage exceeded 1,200 mg/L. Part of the reason may have been that negatively charged colloids were neutralized with the added coagulant, then gradually became positively charged when the optimum dosage was exceeded. They are thus mutually exclusive and not conducive to the aggregation of colloidal particles. Moreover, FeCl₃ addition was studied by comparing addition in one, two and three steps. The total dosage of FeCl₃ remained the same. As shown in Figure 3, the COD removal increased with the increase in dosing steps and addition in three steps was significantly better than one and two steps. COD removal efficiency reached 48.2% when the FeCl₃ loading was 1,000 mg/L and added in three steps.

**UV/H₂O₂/ferrioxalate complexes process studies**

**Effect of initial pH on the UV/Fenton system**

The pH effect was particularly studied through experiments. Figure 4 shows the COD removal from the OFW for different initial pH values. These results also reveal that the UV/Fenton system is a highly pH-sensitive process. Figure 4 shows that COD removal performance declined for pH values greater than 5. This occurs due to the formation of ferric hydroxo-complexes, namely the precipitation of Fe₃⁺ as Fe(OH)₃, hindering the reaction between Fe³⁺ and H₂O₂, and therefore the regeneration of Fe²⁺. Besides, Fe(OH)₃ catalyzes the
self-decomposition of H_2O_2 to molecular oxygen and water, resulting in a decline of its oxidative capacity. When the pH is higher than 8.0 the ferric complexes would further form [Fe(OH)_2]_2^4+ with the generation of flocs and consequent precipitation (Kuo 1992; Bigda 1995). This formation of flocs contributes to a small reduction of COD which occurs at pH 9.0. It is also possible that the precipitation occurs with Fe_3^3+ as oxy-hydroxide amorphous (Fe_2O_3·nH_2O) at pH greater than 3 (Kim et al. 1997). Conversely, for pH values lower than 2.0 the reaction of hydrogen peroxide with Fe_2^2+ is seriously affected due to the formation of the complex species [Fe(H_2O)_6]_2^2+, which reacts more slowly with peroxide compared to [Fe(OH)(H_2O)_5]^2+. In addition, peroxide gets solvated in the presence of high concentration of H^+ ions to form the stable peroxide ion [H_2O_2]^2−. The peroxide ion leads to an electrolytic behaviour on the part of hydrogen peroxide, improving its stability and substantially reducing the reactivity with ferrous ion (Bautista et al. 2007).

Therefore, the initial pH value has to be in the acidic range (3–5) to generate the maximum amount of HO• and oxidize the organic compounds. In particular the optimal value of pH is 4, which is in agreement with previous results obtained in other studies using Fenton’s reagent (Peres et al. 2004).

Effect of n(H_2O_2)/n(Fe_2^2+) on the UV/Fenton System

A favorable n(H_2O_2)/n(Fe_2^2+) molar ratio is worth researching for the UV/Fenton process in this work the molar ratios of n(H_2O_2)/n(Fe_2^2+) ranging from 1:1 to 6:1 were added to evaluate the COD removal and determine the FeSO_4 dosage during the UV/Fenton process. As shown in Figure 5, the COD removal efficiency was significantly influenced by various FeSO_4 dosages. When the molar ratio of n(H_2O_2)/n(Fe_2^2+) increase from 6:1 to 4:1, the COD removal efficiency increased slightly from 58 to 49%. Then, as the increase of Fe_2^2+ concentration, the COD removal efficiency reached a maximum (47.8%) when the n(H_2O_2)/n(Fe_2^2+) increased from 3:1 to 2:1. Moreover, when the n(H_2O_2)/n(Fe_2^2+) was increased to 1:1, the removal efficiency decreased to 36.1%. The reason is mainly due to the relationship between the amount of free radicals generated and Fe_2^2+ content in the reaction system. The radical chain reactions in the Fenton process might be terminated with more Fe_2^2+ in the reaction system. This is because the HO• was produced as a result of the reaction (Equation (6)) then mainly reacts with Fe_2^2+ (Equation (7)) (Neyens & Baeyens 2005; Gádido-Ramírez et al. 2010). Taking the removal efficiency into consideration, the n(H_2O_2)/n(Fe_2^2+) = 2:1 was selected for the UV/Fenton process.

\[
\begin{align*}
\text{H}_2\text{O}_2 + \text{Fe}^{2+} &\rightarrow \text{HO}• + \text{HO}^– \\
\text{HO}• + \text{Fe}^{2+} &\rightarrow \text{Fe}^{3+} + \text{HO}^–
\end{align*}
\]

Effect of H_2O_2 dosage on the UV/Fenton system

Hydrogen peroxide plays a very important role as a source of hydroxyl radicals in the UV/Fenton process. Figure 6 presents the effect of H_2O_2 dosage on COD removal with time under the conditions of n(H_2O_2)/n(Fe_2^2+) of 2 and pH 4. The figure shows that COD removal occurs principally in the initial period (0–30 min), and as the reaction time increased the COD removal approached a plateau under different H_2O_2 dosages. The maximum COD removal was achieved at an H_2O_2 dosage of 0.6% (v/v). Below the optimal H_2O_2 dosage, the oxidation removal efficiency increased with the increase of H_2O_2 dosage because of the increment of ·OH (Equation (6)). Then, continuously increasing the H_2O_2 dosage can reduce the COD removal efficiency, which could be attributed to the scavenger effect of excess H_2O_2. The degradation rate decreased as the H_2O_2 dosage continued to increase beyond the suitable level. The scavenging effect of ·OH by ·OH and the consumption of H_2O_2 by...
this study, 0.6% was selected as the suitable H₂O₂ dosage for the UV/Fenton process.

\[
\cdot\text{OH} + \cdot\text{OH} \rightarrow \text{H}_2\text{O}_2 \quad k_5 = 5.3 \times 10^9 \text{L/mol.s} \quad (8)
\]

\[
\text{H}_2\text{O}_2 + \cdot\text{OH} \rightarrow \text{HO}_2^+ + \text{H}_2\text{O} \quad k_4 = 1.2 \times 10^{10} \text{L/mol.s} \quad (9)
\]

Furthermore, the H₂O₂ dosage can affect the UV/Fenton reaction. First, the form of hydrogen peroxide addition was studied by comparing addition in a single step to that in three steps (with equal volumes) under the H₂O₂ dosage of 0.6% (v/v). As shown in Figure 6, COD removal with H₂O₂ dosage in three steps (47.8%) is better than in one step (43%). The main reason is that multiple additions can make the reagent dispersion more uniform and lead to a more complete reaction. Therefore, the H₂O₂ ought to be added in three steps.

Effect of n(Fe²⁺)/n(C₂O₄²⁻) on the UV/H₂O₂/ferrioxalate complexes system

The effect of the n(Fe²⁺)/n(C₂O₄²⁻) on the removal efficiency of COD is shown in Figure 7(a), where the data derive from a sample at an initial pH of 4, H₂O₂ dosage of 0.6%, n(H₂O₂)/n(Fe²⁺) of 2. The n(Fe²⁺)/n(C₂O₄²⁻) was varied from 0 to 3:1. As shown in Figure 7(a), the COD removal of the UV/H₂O₂/ferrioxalate complexes system reached 55.2%, 13.4% higher than UV/Fenton when the n(Fe²⁺)/n(C₂O₄²⁻) was 3:1. The main reason was that the

![Figure 6](https://iwaponline.com/wst/article-pdf/77/4/909/493982/wst077040909.pdf)

![Figure 7](https://iwaponline.com/wst/article-pdf/77/4/909/493982/wst077040909.pdf)
ferrioxalate complexes could generate more hydroxyl radicals than the UV/Fenton process under UV irradiation and led to rapid oxidative degradation of various organic substances.

Under the UV/H$_2$O$_2$/ferrioxalate complexes system, -OH will be generated through the reaction shown in Equation (6) if the FeSO$_4$ and H$_2$O$_2$ are added first. On the other hand, the ferrioxalate complexes will be formed through the reaction of Fe$^{2+}$ and C$_2$O$_4^{2-}$/C$_0$-$^-$, then quickly react with H$_2$O$_2$ and generate -OH if the FeSO$_4$ and K$_2$C$_2$O$_4$ are added first. The form distribution of ferrioxalate complexes were determined as n(Fe$^{2+}$ or Fe$^{3+}$)/n(C$_2$O$_4^{2-}$/C$_0$-$^-$), and different forms of photoactive ferrioxalate complexes will cause -OH to be generated at different rates. Furthermore, the amount of Fe(C$_2$O$_4$)$_3$/C$_0$-$^-$ produced will be reduced if the K$_2$C$_2$O$_4$ concentration is too low. On the other hand, if excessive, it will generate HCO$_3^-$ and CO$_3^{2-}$/C$_0$-$^-$ in a concentrated K$_2$C$_2$O$_4$ solution, which have a scavenging effect on -OH. Through the reaction between HCO$_3^-$, CO$_3^{2-}$/C$_0$-$^-$ and -OH, the secondary radical generation of HCO$_3^-$ and CO$_3^{2-}$/C$_0$-$^-$ will occur. The secondary radicals generated could react with organics at a relatively low speed. In addition, the photocatalytic decomposition reaction of Fe(C$_2$O$_4$)$_3$/C$_0$-$^-$ will be inhibited if the K$_2$C$_2$O$_4$ concentration is too high. Only if the n(H$_2$O$_2$)/n(Fe$^{2+}$) and n(Fe$^{2+}$)/n(C$_2$O$_4^{2-}$/C$_0$-$^-$) are in a suitable range, will more -OH be obtained.

In this work, the n(Fe$^{2+}$)/n(C$_2$O$_4^{2-}$/C$_0$-$^-$) of 3:1 was selected as the optimum conditions for OFW treated by the UV/H$_2$O$_2$/ferrioxalate complexes process.

Neutralization and flocculation studies

After the coagulation/UV/H$_2$O$_2$/ferrioxalate complexes process, a large number of iron ions dissolved in the wastewater. When NaOH was added to the wastewater to adjust the pH to 8.5–9, some Fe$^{3+}$ will be converted into Fe(OH)$_3$, which is considered an excellent chemical coagulant. Then, adding an appropriate amount of CPAM led to the formation of large precipitates immediately. After standing for 30 min, the water was filtered through a membrane (0.45 μm) using vacuum suction filter. As shown in Figure 7(b), the COD removal efficiency increased with the increase of CPAM dosage from 0 to 2 mg/L, and then decreased when the CPAM dosage exceeded 2 mg/L. The reason is that the reaction mechanisms of CPAM include the interaction of hydroxides, neutralization, precipitation and accumulation (Divakaran et al. 2001) at the suitable dosage, thus removed the COD. Nevertheless, CPAM itself acts as the organic matter, and in turn can increase the organic content when overused. So the optimal CPAM dosage obtained was 2 mg/L, with a 30.2% reduction in the COD during the single process.

Coagulation and UV/H$_2$O$_2$/ferrioxalate complexes process

Based on the optimization of the coagulation and UV/H$_2$O$_2$/ferrioxalate complexes process, the initial OFW was first subjected to a coagulation process. Subsequently, the supernatant was withdrawn and subjected to the UV/H$_2$O$_2$/ferrioxalate complexes process. All experimental parameters were controlled under individual selected conditions. The characteristics of the coagulant and UV/H$_2$O$_2$/ferrioxalate complexes processes and effluents, as well as the overall treatment efficiency are summarized in Figure 8. A total of 48.2% COD could be removed in the coagulation process at pH 4, dilution ratio of raw OFW of 1:2 and FeCl$_3$ dosage of 1,000 mg/L, whereas 30.1% COD was removed in the UV/H$_2$O$_2$/ferrioxalate complexes process at pH 4, at H$_2$O$_2$ dosage of 0.6% (v/v), n(H$_2$O$_2$)/n(Fe$^{2+}$) of 2:1 and n(Fe$^{2+}$)/n(C$_2$O$_4^{2-}$/C$_0$-$^-$) of 3:1. Furthermore, 30.4% COD was removed in the neutralization and flocculation process at pH 8.5–9 and CPAM dosage of 2 mg/L.

Table 2 | Main parameters of the wastewater before and after the proposed treatment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before treatment</th>
<th>After treatment</th>
<th>Removal (%)</th>
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<tr>
<td>COD (mg/L)</td>
<td>1,440</td>
<td>233</td>
<td>83.8</td>
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<tr>
<td>Suspended solids (mg/L)</td>
<td>192</td>
<td>12.3</td>
<td>93.6</td>
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<tr>
<td>Oil and grease (mg/L)</td>
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<td>4.7</td>
<td>75.5</td>
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<td>Color (°)</td>
<td>55</td>
<td>6.9</td>
<td>87.5</td>
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</tbody>
</table>
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Table 3 | Comparison of COD removal from wastewater under different advanced oxidation processes

<table>
<thead>
<tr>
<th>Process</th>
<th>COD (mg/L)</th>
<th>pH</th>
<th>Operating parameters</th>
<th>COD removal (%)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floc/Fenton</td>
<td>9,360</td>
<td>6.35</td>
<td>[PAC] = 40 mg/L, [PAM] = 4 mg/L, dilution ratio = 1:2, stirring time = 30 min; [H$_2$O$_2$] = 2 mmol/L, [n(H$_2$O$_2$)/n (FeSO$_4$)$_3$] = 2, reaction time = 60 min</td>
<td>76.6</td>
<td>Jia et al. (2012)</td>
</tr>
<tr>
<td>Oxone/O$_2$</td>
<td>1,116</td>
<td>8.17</td>
<td>[Oxone] = 4.5 mM, [Co$^{2+}$] = 0.45 μm, pH$_o$ = 6.5, V = 0.1 L, 30 °C</td>
<td>57.5</td>
<td>Sun et al. (2009)</td>
</tr>
<tr>
<td>O$_2$/PDS</td>
<td>2,500</td>
<td>8.5</td>
<td>[PDS] = 91.14 mM, [O$_3$] = 80 mg/L, pH$_o$ = 10, V = 2 L, 15 °C</td>
<td>72</td>
<td>Abu Amr et al. (2015)</td>
</tr>
<tr>
<td>O$_2$/H$_2$O$_2$/Fe$^{2+}$</td>
<td>2,180</td>
<td>8.5</td>
<td>[H$_2$O$_2$] = 50 mM, [Fe$^{2+}$] = 50 mM, [O$_3$] = 80 mg/L, pH$_o$ = 7, V = 2 L, 15 °C</td>
<td>6</td>
<td>Abu Amr et al. (2012)</td>
</tr>
<tr>
<td>Fenton</td>
<td>1,116</td>
<td>8.17</td>
<td>[H$_2$O$_2$] = 80 mM, [Fe$^{2+}$] = 40 mM, pH$_o$ = 2.5, V = 1:2, stirring time = 30 s, [H$_2$O$_2$] = 4.0 mol/L, pH$_o$ = 0.6%(v/v), UV = 100 W for 30 s</td>
<td>56</td>
<td>Shi et al. (2009)</td>
</tr>
<tr>
<td>UV/H$_2$O$_2$/Fe$^{2+}$</td>
<td>1,560</td>
<td>/</td>
<td>[H$_2$O$_2$] = 0.6 mol/L, [Fe$^{2+}$] = 3.0 mol/L, pH$_o$ = 7, 25 °C</td>
<td>73.4</td>
<td>Chen et al. (2014)</td>
</tr>
<tr>
<td>Floc/UV/H$_2$O$_2$</td>
<td>3,332</td>
<td>8.3</td>
<td>[FeCl$_3$] = 1,400 mg/L, pH = 4.0, rapid mixing at 400 rpm, for 30 s; [H$_2$O$_2$] = 1,500 mg/L, pH = 4.0, UV = 25 W</td>
<td>71.9</td>
<td>Ana et al. (2014)</td>
</tr>
<tr>
<td>Coag/UV/H$_2$O$_2$/ferrioxalate complexes</td>
<td>4,069–4,386</td>
<td>6.5</td>
<td>[FeCl$_3$] = 1,000 mg/L, dilution ratio = 1:2, pH = 4.0, in three steps: pH = 4.0, n([H$_2$O$_2$]/n(Fe$^{2+}$)) = 1, n([PAM]/n(C$_2$O$_4^{2-}$)) = 1, pH = 3.75, V = 0.1 L, 25 W</td>
<td>83.8</td>
<td>This study</td>
</tr>
</tbody>
</table>

REFERENCES


ACKNOWLEDGEMENTS

The authors thank the kind help of China National Offshore Oil Corporation in Tianjin in providing water samples.
Withdrawn


First received 14 June 2017; accepted in revised form 20 November 2017. Available online 1 December 2017

Withdrawn