Decolorization of an azo dye Orange G in aqueous solution by Fenton oxidation process: Effect of system parameters and kinetic study

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A R T I C L E   I N F O

A B S T R A C T

To establish cost-efficient operating conditions for potential application of Fenton oxidation process to treat wastewater containing an azo dye Orange G (OG), some important operating parameters such as pH value of solutions, dosages of H_2O_2 and Fe^{2+}, temperature, presence/absence of chloride ion and concentration of the dye, which effect on the decolorization of OG in aqueous solution by Fenton oxidation have been investigated systematically. In addition, the decolorization kinetics of OG was also elucidated based on the experimental data. The results showed that a suitable decolorization condition was selected as initial pH 4.0, H_2O_2 dosage 1.0×10^{-2} M and molar ratio of $[H_2O_2]/[Fe^{2+}]$ 286:1. The decolorization of OG enhanced with the increasing of reaction temperature but decreased as a presence of chloride ion. On the given conditions, for 2.21×10^{-5} to 1.11×10^{-4} M of OG, the decolorization efficiencies within 60 min were more than 94.6%. The decolorization kinetics of OG by Fenton oxidation process followed the second-order reaction kinetics, and the apparent activation energy E, was detected to be 34.84 kJ mol^{-1}. The results can provide fundamental knowledge for the treatment of wastewater containing OG and/or other azo dyes by Fenton oxidation process.
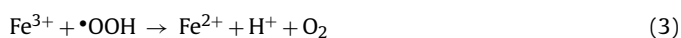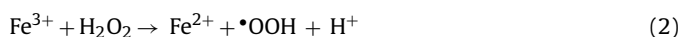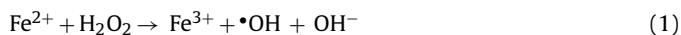
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1. Introduction

Dye pollutants from the dyestuff manufacturing, dyeing, printing and textile industries are important sources of environmental contamination. The effluents discharged from these industries are usually strongly colored, and the direct release of the wastewater into receiving water body will cause damage to both aquatic life and human beings due to their toxic, carcinogenic and mutagenic effects [1,2]. Azo dyes, characterized by the presence of one or more azo groups (—N=N—) bound to aromatic rings, are the largest and most important class of synthetic organic dyes. It has been estimated that more than 50% of all dyes in common use are azo dyes because of their chemical stability and versatility [3]. The complex and steady molecular structures render most of azo dyes resistant to biological or even chemical degradation, which result in the conventional physical, chemical and biological treatment methods inefficient and costly for the removal of them from water.

Fenton's reaction is a homogeneous catalytic oxidation process using a mixture of hydrogen peroxide (H_2O_2) and ferrous ions (Fe^{2+}) in an acidic medium, which was firstly discovered by Fenton in the 1890s [4]. In the last decades, Fenton's reaction has been introduced into wastewater treatment processes, and it has been well proven that a variety of refractory organics could be effectively degraded through Fenton's reaction without producing any toxic substances in water environment [5,6]. The mechanism that describe Fenton's reaction mainly includes the following reactions [5,7]:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {}^\bullet OH + OH^- \tag{1}$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + {}^\bullet OOH + H^+ \tag{2}$$

$$Fe^{3+} + {}^\bullet OOH \rightarrow Fe^{2+} + H^+ + O_2 \tag{3}$$

$${}^\bullet OH + H_2O_2 \rightarrow {}^\bullet OOH + H_2O \tag{4}$$

$${}^\bullet OH + Fe^{2+} \rightarrow Fe^{3+} + OH^- \tag{5}$$

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$$\bullet OH + \bullet OH \rightarrow H_2O_2 \tag{6}$$

$$\bullet OH + \bullet OOH \rightarrow O_2 + H_2O \tag{7}$$

In the process, hydroxyl radicals ($\bullet OH$), which is the second strongest oxidant ($E° = 2.87$ V, versus normal hydrogen electrode (NHE)), only inferior to fluoride ($E° = 3.06$ V) was produced. Hydroxyl radicals can rapidly and non-selectively react with a wide range of organic pollutants through hydrogen abstraction, electrophilic addition and/or electron transfer to mineralize them to CO_2, H_2O and inorganic ions [8]. There are several studies related to using of Fenton oxidation process for the treatment of azo dyes wastewaters [9–12]. The previous researches have shown that a number of azo dyes could be effectively degraded by Fenton oxidation. And the decolorization efficiency of dyes was mainly depended on their chemical characteristics, the generation rate and concentration of $\bullet OH$ in the process.

In this study, research was carried out to investigate the decolorization of an azo dye named Orange G (OG) by Fenton oxidation process. The chemical characteristics of the dye were illustrated in Table 1. Hsueh et al. [9] have reported that OG could be effectively degraded by Fenton-like (H_2O_2/Fe^{3+}) system, but the effects of various operation conditions on the decolorization of OG by Fenton oxidation were not systematically investigated. In addition, the information regarding the decolorization kinetics of OG by Fenton oxidation is also very limited. Therefore, the aim of this study is to investigate the influence of some important operating parameters such as pH value of solutions, dosages of H_2O_2 and Fe^{2+}, temperature and presence/absence of chloride ion on the decolorization of OG in aqueous solution. And further to establish cost-efficient operating conditions for the potential application of Fenton oxidation process to treat wastewater containing OG. Furthermore, the decolorization kinetics of OG was also elucidated based on the experimental data. The results can provide fundamental knowledge for the treatment of wastewater containing OG by Fenton oxidation process.

2. Experimental

2.1. Materials

Azo dye OG, hydrogen peroxide (30% w/w), ferrous sulfate ($FeSO_4 \bullet 7H_2O$), sulfuric acid, sodium hydroxide and sodium chloride were all obtained from Shanghai Chemical Reagents Co. (Shanghai, China). All of chemicals used were analytical grade without any further purification. Deionized water was used throughout this study.

2.2. Experimental procedures

All tests were conducted in a 200 mL double glass cylindrical jacket reactor, which allows cycle water to maintain the temperature of the reaction mixture constant. Temperature control was realized through a thermostat and a magnetic stirrer was used to stir reaction solutions. To start each test, appropriate volumes of stock OG solutions and ferrous sulfate solutions were placed into the reactor and then diluted with deionized water to 100 mL. The pH value of each reaction solution was adjusted to the desired value by using the prepared 1.0 M sulfuric acid or 1.0 M sodium hydroxide solution, and was measured with a model PHS-3C pH meter. The reactions were initiated by adding calculated amounts of hydrogen peroxide to the reactor. Samples were taken out from the reactor periodically using a pipette and were analyzed immediately.

2.3. Analytical methods

The UV–vis spectra of OG were recorded from 200 to 800 nm using a UV/Vis spectrophotometer (Lambda 17, Perkin-Elmer) with a spectrometric quartz cell (1 cm path length). The maximum absorbance wavelength (λ_{max}) of OG was found at 478 nm. The peak at 478 nm was attributed to the absorption of the $n \rightarrow \pi^*$ transition related to the $-N=N-$ group in OG molecule. In the whole reaction process, it was found that the measure of OG concentration is not interfered by the degradation products. Therefore, the concentration of OG in reaction mixture at different reaction times was determined by measuring the absorption intensity of solution at 478 nm and using a calibration curve. The reaction could continue after sampling, so in order to decrease the experimental error, the sampling and measurement of the absorbance of reaction solutions were finished in 1 min [13].

3. Results and discussion

3.1. Optimization of system parameters

3.1.1. Effect of initial pH on the decolorization of OG

The effect of initial pH value of solutions on the decolorization of OG by Fenton oxidation process was studied in the pH range of 2.5–6.0 and the results were shown in Fig. 1. A direct influence of initial pH on the decolorization of OG could be observed and the best decolorization efficiency was obtained at pH of 4.0. At initial pH of 6.0, the decolorization of OG almost could not be observed in 60 min of reaction. It is principally due to the formation of ferrous/ferric hydroxide complexes lead to the deactivation of ferrous catalyst, which result in the amount of $\bullet OH$ generated was very small [14,15]. When the initial pH was decreased from 6.0 to 4.0, the decolorization efficiency of OG within 60 min increased significantly from 0.8% to 94.7%. However, the decolorization efficiency of OG slowed down to 70.8% as a further decrease of the initial pH from 4.0 to 2.5. This could be explained by the formation of oxonium ion (i. e. $H_3O_2^+$), which enhanced the stability of H_2O_2 and restricted the generation of $\bullet OH$ at low pH conditions (pH < 3.0) [16]. In addition, the scavenging of $\bullet OH$ by the excessive of H^+ is also another reason for the lower decolorization efficiency of OG at pH of 2.5 [14,17]. Herein, a suitable initial pH for the decolorization of OG by Fenton oxidation process was recommended as 4.0.
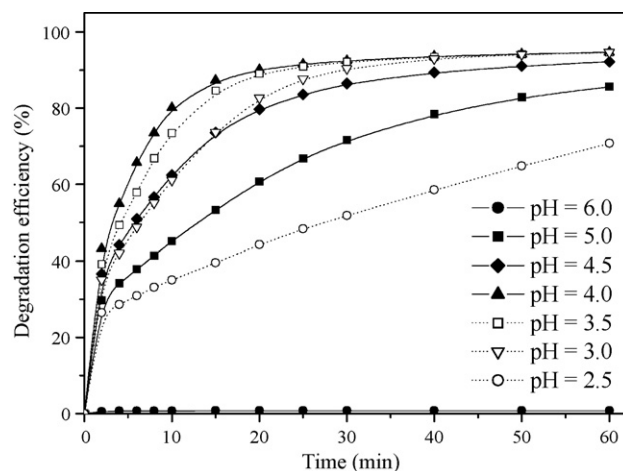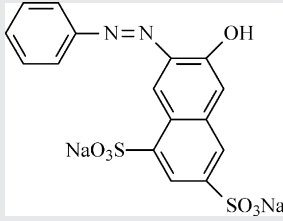

Fig. 1. Effect of initial pH values on the decolorization of OG by Fenton oxidation. Experimental conditions: [OG] = 6.63×10^{-5} M; [H_2O_2] = 1.0×10^{-2} M; [Fe^{2+}] = 3.5×10^{-5} M; temperature = 20 °C.

Table 1
Chemical characteristics of Orange G

Dye	Chemical structure	Molecular formula	Molecular weight ($g\,mol^{-1}$)	λ_{max} (nm)
Orange G		$C_{16}H_{10}N_2Na_2O_7S_2$	452.36	478

3.1.2. Effect of H_2O_2 dosage on the decolorization of OG

H_2O_2 plays a very important role as a source of $^\bullet$OH generation in Fenton's reaction. The effect of H_2O_2 dosage on the decolorization of OG was examined by varying initial concentration of H_2O_2 from 1.0×10^{-3} to 4.0×10^{-2} M and the results were shown in Fig. 2. From the figure, it can be observed that increasing the dosage of H_2O_2 from 1.0×10^{-3} to 1.0×10^{-2} M could enhance the decolorization of OG from 74.2% to 92.5% within 30 min of reaction. However, when further increase of the dosage above 1.0×10^{-2} M, the decolorization of OG was not improved but dropped down. For example, the decolorization efficiencies within 10 min of reaction reduced from 80.2% to 74.6% as an increasing dosage of H_2O_2 from 1.0×10^{-2} to 4.0×10^{-2} M. Indeed, the decrease of the decolorization efficiency of OG at high dosage of H_2O_2 was mainly caused by the scavenging effect of excessive H_2O_2 to $^\bullet$OH (Eq. (4)). In addition, the recombination of $^\bullet$OH (Eq. (6)) also contributed for the declining of the decolorization efficiency of OG [5,7]. From the experimental results, therefore, it was selected a suitable H_2O_2 dosage as 1.0×10^{-2} M.

3.1.3. Effect of Fe^{2+} dosage on the decolorization of OG

Fe^{2+} is another main parameter in Fenton's reaction that catalytically decomposes H_2O_2 to generate $^\bullet$OH. Fig. 3 showed the effect of Fe^{2+} dosage on the decolorization of OG with different initial concentration from 5.0×10^{-6} to 3.5×10^{-5} M. It can be seen that the decolorization was limited at 5.0×10^{-6} M of Fe^{2+}, and only 52.5% of OG was degraded within 60 min of reaction. In the presence of 1.5×10^{-5}, 2.5×10^{-5} and 3.5×10^{-5} M of Fe^{2+}, a great improvement of the decolorization of OG could be observed and the decolorization efficiencies within 60 min of
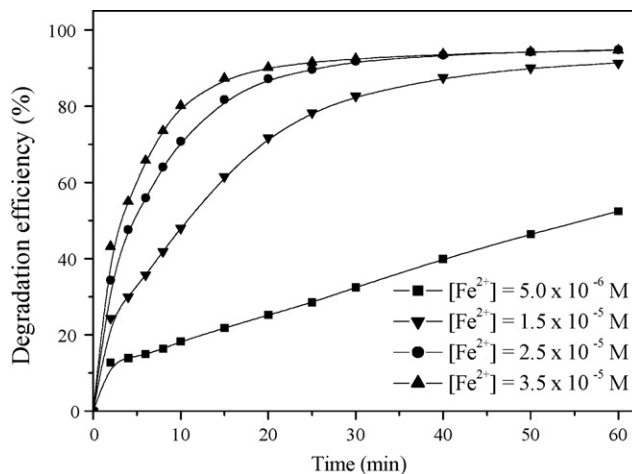

Fig. 3. Effect of Fe^{2+} dosage on the decolorization of OG by Fenton oxidation. Experimental conditions: [OG] = 6.63×10^{-5} M; [H_2O_2] = 1.0×10^{-2} M; pH = 4.0; temperature = 20 °C.

reaction achieved were 82.8%, 91.8% and 92.5%, respectively. The fact that higher decolorization efficiency achieved at high Fe^{2+} dosages was mainly attribute to the higher production of $^\bullet$OH with more Fe^{2+} in Fenton's reaction. Herein, 3.5×10^{-5} M of Fe^{2+} was considered to be a suitable dosage for the decolorization of OG.

In fact, it is important to detect the optimum molar ratio of [H_2O_2]/[Fe^{2+}], because the ratio can directly affect the production of $^\bullet$OH in Fenton's reaction. According to the literature, there is still
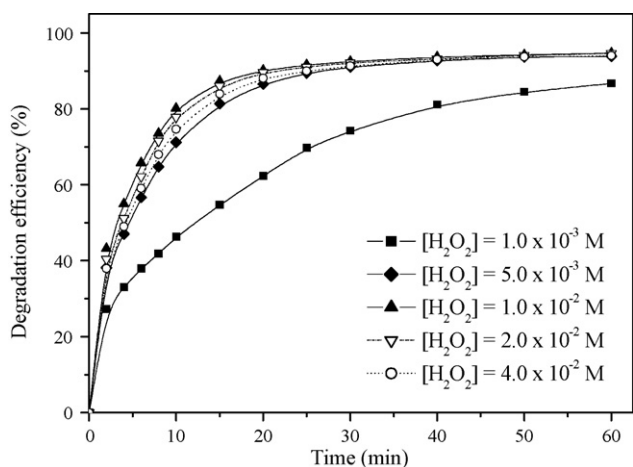

Fig. 2. Effect of H_2O_2 dosage on the decolorization of OG by Fenton oxidation. Experimental conditions: [OG] = 6.63×10^{-5} M; [Fe^{2+}] = 3.5×10^{-5} M; pH = 4.0; temperature = 20 °C.
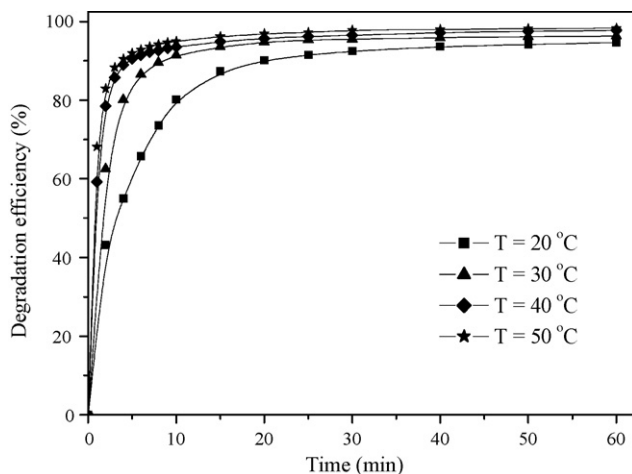

Fig. 4. Effect of temperature on the decolorization of OG by Fenton oxidation. Experimental conditions: [OG] = 6.63×10^{-5} M; [H_2O_2] = 1.0×10^{-2} M; [Fe^{2+}] = 3.5×10^{-5} M; pH = 4.0.
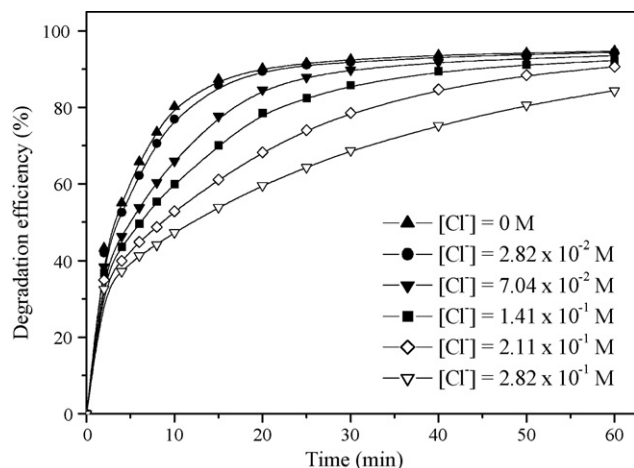
Fig. 5. Effect of chloride ion on the decolorization of OG by Fenton oxidation. Experimental conditions: $[OG] = 6.63 \times 10^{-5}$ M; $[H_2O_2] = 1.0 \times 10^{-2}$ M; $[Fe^{2+}] = 3.5 \times 10^{-5}$ M; pH = 4.0; temperature = 20 °C.

no agreement on the optimum molar ratio of $[H_2O_2]/[Fe^{2+}]$ for the treatment of various wastewaters by Fenton oxidation process. Different optimum molar ratio of $[H_2O_2]/[Fe^{2+}]$ has been proposed for the degradation of different pollutants in aqueous solution covering the range of 1:1 to 400:1 [18]. In present study, a suitable molar ratio of $[H_2O_2]/[Fe^{2+}]$ for the decolorization of OG was experimentally detected as 286:1.

3.1.4. Effect of temperature on the decolorization of OG

The effect of temperature on the decolorization of OG was studied at different temperatures of 20, 30, 40 and 50 °C, and the results were shown in Fig. 4. As can be seen from the Fig. 4, raising the temperature has a positive impact on the decolorization of OG. The decolorization efficiency within 10 min of reaction increased from 80.2% to 95.1% as an increasing the temperature from 20 to 50 °C. Additionally, the period of time required for the decolorization of OG was also much shorter at higher temperature. This can be explained that Fenton's reaction could be accelerated by raising temperature which improved the generation rate of $^{\bullet}$OH and therefore to enhance the decolorization of OG.

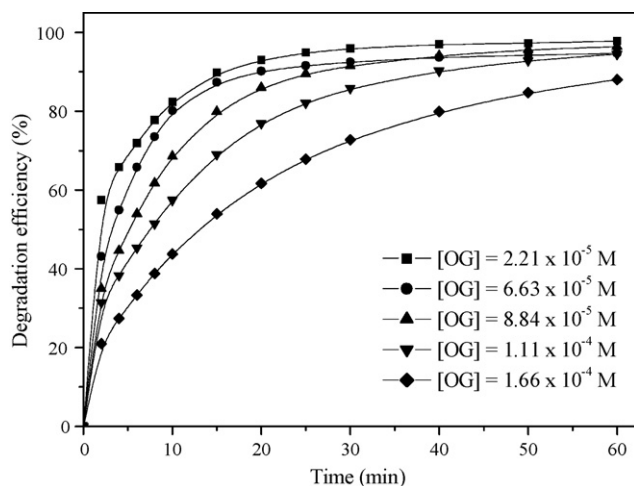**Fig. 6.** Effect of OG concentration on the decolorization of OG by Fenton oxidation. Experimental conditions: $[H_2O_2] = 1.0 \times 10^{-2}$ M; $[Fe^{2+}] = 3.5 \times 10^{-5}$ M; pH = 4.0; temperature = 20 °C.
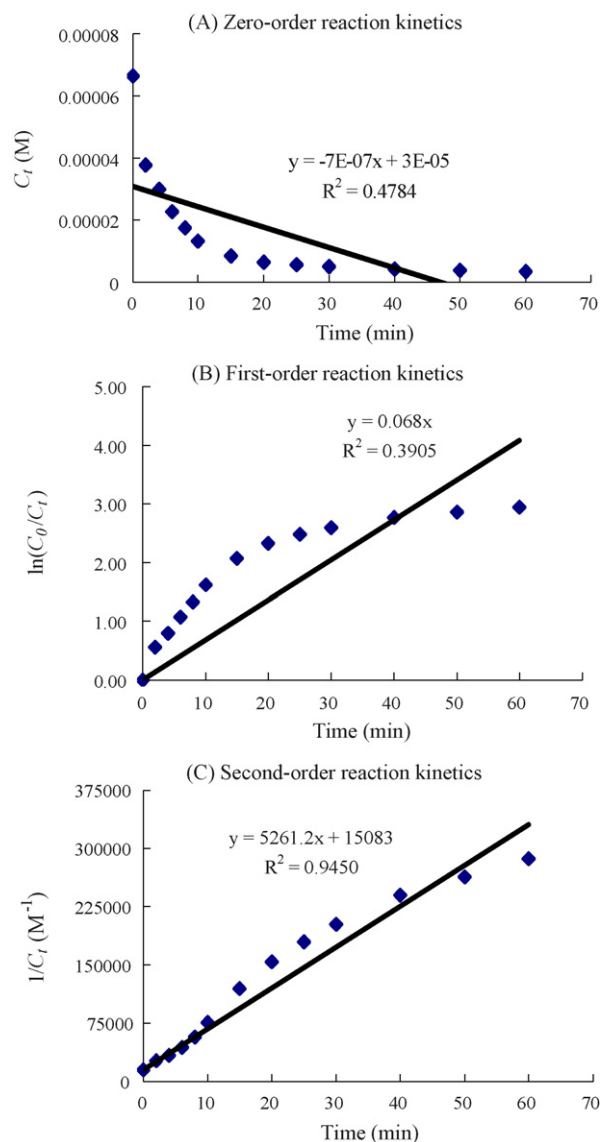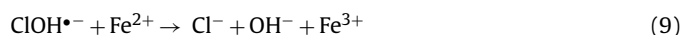

Fig. 7. (A) Zero-, (B) first- and (C) second-order reaction kinetics for the decolorization of OG by Fenton oxidation. Experimental conditions: $[OG] = 6.63 \times 10^{-5}$ M; $[H_2O_2] = 1.0 \times 10^{-2}$ M; $[Fe^{2+}] = 3.5 \times 10^{-5}$ M; pH = 4.0; temperature = 20 °C.

3.1.5. Effect of chloride ion on the decolorization of OG

Huge amounts of salts were used in coloring up variety of dyes on textiles and they were co-existed with dyes in effluent, which could affect the treatment of wastewater. In the present study, the effect of the presence of chloride ion (2.82×10^{-2} to 2.82×10^{-1} M) on the decolorization of OG was investigated and the results were shown in Fig. 5. It can be seen that chloride ion had a negative impact on the decolorization of OG by Fenton oxidation. The decolorization efficiency within 60 min reaction decreased from 94.7% to 84.5% as a consequence of increasing the concentration of chloride ions from 0 to 2.82×10^{-1} M, and therefore about 10% of decolorization efficiency was lost. The inhibitive effect of chloride ions on the decolorization of OG can be explained by the scavenging effect of chloride ion to $^{\bullet}$OH, and the chemical reactions were shown as below (Eq. (8) and Eq. (9)) [19].

$$Cl^- + {}^{\bullet}OH \rightarrow ClOH^{\bullet -} \tag{8}$$

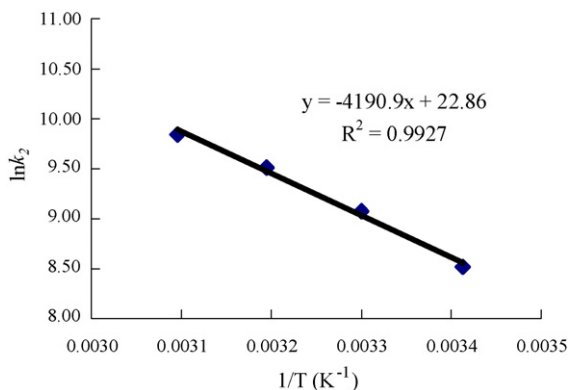$$ClOH^{\bullet -} + Fe^{2+} \rightarrow Cl^- + OH^- + Fe^{3+} \tag{9}$$

Fig. 8. The Arrhenius plot of $\ln k_2$ versus $1/T$ of the decolorization of OG by Fenton oxidation. Experimental conditions: $[OG] = 6.63 \times 10^{-5}$ M; $[H_2O_2] = 1.0 \times 10^{-2}$ M; $[Fe^{2+}] = 3.5 \times 10^{-5}$ M; pH = 4.0.

3.1.6. Effect of concentration of OG on the decolorization of OG

The decolorization of different concentration of OG was studied, and the results were shown in Fig. 6. It can be seen that the decolorization efficiency of OG was decreased with the increasing concentration of OG. As increasing of the concentration OG from 2.21×10^{-5} to 1.66×10^{-4} M, the decolorization efficiency of OG within 30 min of reaction decreased from 96.0% to 72.8%. This is due to that a relative lower concentration of $\bullet OH$ results from the increasing concentration of OG but the same dosage of H_2O_2 and Fe^{2+}, which led to a decreasing of the decolorization efficiency of OG. However, the decolorization efficiency within 60 min reaction was also achieved to 94.6% when the OG's concentration was 1.11×10^{-4} M.

3.2. Kinetic study

In the present study, zero-, first- and second-order reaction kinetics were used to study the decolorization kinetics of OG by Fenton oxidation process. The individual expression was presented as below (Eqs. (10) and (11)):

Zero-order reaction kinetics:

$$\frac{dc}{dt} = -k_0 \tag{10}$$

First-order reaction kinetics:

$$\frac{dc}{dt} = -k_1 C \tag{11}$$

Second-order reaction kinetics:

$$\frac{dc}{dt} = -k_2 C^2 \tag{12}$$

where C is the concentration of OG; k_0, k_1 and k_2 represent the apparent kinetic rate constants of zero-, first- and second-order reaction kinetics, respectively; t is the reaction time.

By integrating the Eqs. (10)–(12), the following equations could be obtained (Eqs. (13)–(15)):

$$C_t = C_0 - k_0 t \tag{13}$$

$$C_t = C_0 e^{-k_1 t} \tag{14}$$

$$\frac{1}{C_t} = \frac{1}{C_0} + k_2 t \tag{15}$$

where C_t is the concentration of OG at reaction time t.

Regression analysis based on the zero-, first- and second-order reaction kinetics for the decolorization of OG in Fenton oxidation process was conducted and the results were shown in Fig. 7. Comparing the regression coefficients (R^2) obtained from Fig. 7(A)–(C), it can be seen that R^2 based on the second-order reaction kinetics (Fig. 7(C)) was 0.9450, which was obviously much better than that based on the zero-order ($R^2 = 0.4784$) and the first-order ($R^2 = 0.3905$) reaction kinetics. The results indicated that the decolorization kinetics of OG followed the second-order kinetics well. Based on the above analysis, the second-order kinetic rate constants for the decolorization of OG at different reaction conditions were obtained and the results were shown in Table 2. In the present

Table 2
The second-order kinetic rate constants for the decolorization of OG at different reaction conditions

No.	[OG] (M)	pH	[H₂O₂] (M)	[Fe²⁺] (M)	Temperature (°C)	[Cl⁻] (M)	Second-order reaction kinetics	
							k_2 (M^{-1} min^{-1})	R^2
1	6.63×10^{-5}	5.0	1.0×10^{-2}	3.5×10^{-5}	20	0	1.41×10^3	0.9849
2	6.63×10^{-5}	4.5	1.0×10^{-2}	3.5×10^{-5}	20	0	3.07×10^3	0.9965
3	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	0	5.26×10^3	0.9450
4	6.63×10^{-5}	3.5	1.0×10^{-2}	3.5×10^{-5}	20	0	5.03×10^3	0.9662
5	6.63×10^{-5}	3.0	1.0×10^{-2}	3.5×10^{-5}	20	0	4.60×10^3	0.9748
6	6.63×10^{-5}	2.5	1.0×10^{-2}	3.5×10^{-5}	20	0	5.84×10^2	0.9457
7	6.63×10^{-5}	4.0	1.0×10^{-3}	3.5×10^{-5}	20	0	1.58×10^3	0.9869
8	6.63×10^{-5}	4.0	5.0×10^{-3}	3.5×10^{-5}	20	0	4.41×10^3	0.9708
9	6.63×10^{-5}	4.0	2.0×10^{-2}	3.5×10^{-5}	20	0	5.03×10^3	0.9610
10	6.63×10^{-5}	4.0	4.0×10^{-2}	3.5×10^{-5}	20	0	4.57×10^3	0.9640
11	6.63×10^{-5}	4.0	1.0×10^{-2}	5.0×10^{-6}	20	0	2.66×10^2	0.9676
12	6.63×10^{-5}	4.0	1.0×10^{-2}	1.5×10^{-5}	20	0	2.56×10^3	0.9742
13	6.63×10^{-5}	4.0	1.0×10^{-2}	2.5×10^{-5}	20	0	4.99×10^3	0.9859
14	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	30	0	8.72×10^3	0.7473
15	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	40	0	1.35×10^4	0.8820
16	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	50	0	1.88×10^4	0.8948
17	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	2.82×10^{-2}	4.87×10^3	0.9528
18	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	7.04×10^{-2}	3.92×10^3	0.9842
19	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	1.41×10^{-1}	3.02×10^3	0.9923
20	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	2.11×10^{-1}	2.20×10^3	0.9684
21	6.63×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	2.82×10^{-1}	1.26×10^3	0.9769
22	2.21×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	0	3.40×10^4	0.9858
23	8.84×10^{-5}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	0	4.67×10^3	0.9666
24	1.11×10^{-4}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	0	2.24×10^3	0.9473
25	1.66×10^{-4}	4.0	1.0×10^{-2}	3.5×10^{-5}	20	0	6.47×10^2	0.9631

study, it can be concluded that the decolorization of OG by Fenton oxidation fits the second-order reaction kinetic of the type:

$$-r_{[OG]} \approx k_2[OG]^2 \tag{16}$$

The apparent kinetic rate constants, k_2, of the decolorization of OG was found to be $5.26 \times 10^3\,M^{-1}\,min^{-1}$ at an optimal condition of $[OG] = 6.63 \times 10^{-5}\,M$, $[H_2O_2] = 1.0 \times 10^{-2}\,M$, $[Fe^{2+}] = 3.5 \times 10^{-5}\,M$, pH = 4.0 and 20 °C.

According to the apparent kinetic rate constants at different temperatures, the apparent activation energy E, for the decolorization of OG by Fenton oxidation was computed with Arrhenius equation (Eq. (17)).

$$k = A \exp\left(-\frac{E}{RT}\right) \tag{17}$$

where A is the preexponential (or frequency) factor; E is the apparent activation energy ($J\,mol^{-1}$); R is the ideal gas constant ($8.314\,J\,mol^{-1}\,K^{-1}$); T is the reaction absolute temperature (K). The Arrhenius plot of $\ln k_2$ versus $1/T$ was shown in Fig. 8. It can be seen that a good linear relationship existed in the plots of $\ln k_2$ versus $1/T$ ($R^2 > 0.99$). The apparent activation energy E, obtained from the Arrhenius type plot in Fig. 8 was found to be $34.84\,kJ\,mol^{-1}$, and A value was $8.47 \times 10^9\,M^{-1}\,min^{-1}$. Generally, the reaction activation energy of ordinary thermal reactions is usually between $60\,kJ\,mol^{-1}$ and $250\,kJ\,mol^{-1}$ [20], the result implies that the decolorization of OG in aqueous solution by Fenton oxidation process requires lower activation energy and can be easily achieved.

4. Conclusions

In this work, the decolorization of OG in aqueous solution by Fenton oxidation process has been studied on different experimental conditions, including different pH value of solutions, dosages of H_2O_2 and Fe^{2+}, temperature, presence/absence of chloride ion and different of dye concentration. A suitable operating condition was selected as: $[OG] = 2.21 \times 10^{-5}$ to $1.11 \times 10^{-4}\,M$, $[H_2O_2] = 1.0 \times 10^{-2}\,M$, $[Fe^{2+}] = 3.5 \times 10^{-5}\,M$, pH = 4.0 and temperature at 20 °C. In the given conditions, more than 94.6% of decolorization efficiency was achieved within 60 min of reaction. In addition, it was found that the decolorization efficiency of OG enhanced with the increasing of reaction temperature but the presence of chloride ion had a negative impact on the decolorization of OG. The kinetics study indicated that the decolorization kinetics of OG followed the second-order kinetics well. The apparent activation energy E, for the decolorization of OG by Fenton oxidation was determined to be $34.84\,kJ\,mol^{-1}$.

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