

Removal of COD from laundry wastewater by electrocoagulation/electroflotation

Chih-Ta Wang^{a,*}, Wei-Lung Chou^b, Yi-Ming Kuo^a

^a Department of Safety Health and Environmental Engineering, Chung Hwa University of Medical Technology, Tainan County, Hsien 717, Taiwan

^b Department of Safety Health and Environmental Engineering & Institute of Occupational Safety and Hazard Prevention, Hungkuang University, Sha-Lu, Taichung 433, Taiwan

ARTICLE INFO

Article history:

Received 18 March 2008

Received in revised form 25 June 2008

Accepted 28 July 2008

Available online 3 August 2008

Keywords:

Electrocoagulation

Electroflotation

Laundry wastewater

Ultrasound

COD removal

ABSTRACT

The removal efficiency of COD in the treatment of simulated laundry wastewater using electrocoagulation/electroflotation technology is described. The experimental results showed that the removal efficiency was better, reaching to about 62%, when applying ultrasound to the electrocoagulation cell. The solution pH approached neutrality in all experimental runs. The optimal removal efficiency of COD was obtained by using the applied voltage of 5 V when considering the energy efficiency and the acceptable removal efficiency simultaneously. The Cl^- concentration of less than 2500 ppm had a positive effect on the removal efficiency. The performance of the monopolar connection of electrodes was better than that of the bipolar connection in this work. In addition, the removal efficiency of using Al electrodes was higher in comparison with using Fe electrodes in the study. The highest COD removal amount per joule was found to be $999 \text{ mg dm}^{-3} \text{ kW h}^{-1}$ while using two Al electrodes, although the removal efficiency increased with the number of Al plates.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

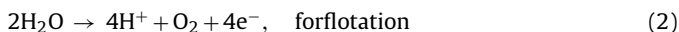
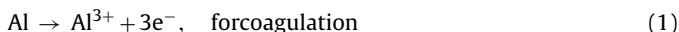
The untreated wastewater from coin-operated laundry processes is now a major pollution source for rivers in Taiwan. The most widely used methods, such as traditional coagulation, flotation, adsorption and chemical oxidation or combination of these are insufficient for laundry wastewater treatment. Because of the large variability of the amount and composition of laundry wastewater, developing a new treatment method is necessary. Recently, the electrochemical technology is popular in treating wastewater due to its safe and environmentally friendly nature. The electrochemical techniques are effective in treating wastewater containing several organic and inorganic compounds, including phenol, dyes, metal ions, cyanide, etc., because various degradation and removal mechanisms may exist simultaneously in an electrochemical reactor [1–3]. In the past, electrochemical oxidation technique was usually employed to degrade surfactants in wastewater, as investigated by several authors [4,5]. Leu et al. [4] reported that the linear alkyl sulfonates (LAS) and alkylbenzene sulfonates (ABS) could be completely removed by indirect electrochemical oxidation in conjunction with chemical coagu-

lation. Lissen et al. [5] used BDD and graphite electrodes to degrade two surfactants in dilute solution. They found that the process was not diffusion-controlled. Though the surfactants can be effectively removed by the electrochemical oxidation, the instantaneous current efficiencies were very low, varying from 5% to 12%.

Among the electrochemical technologies, electrocoagulation and electroflotation may be effective substitutions for conventional coagulation and flotation in a wastewater treatment process [6]. Electrocoagulation/electroflotation has been reported to successfully treat wastewater of different kinds, containing oil [7,8], fluoride [9], arsenic [10], dyes [11–16], suspended particles [17], surfactants [18], chromium ions [19], phosphate [20,21] and so on. Electrocoagulation is an electrochemical technology of treating polluted water whereby sacrificial anodes dissolve due to an applied potential, thus producing active coagulant precursors. Electrocoagulation is a complicated process with a multitude of mechanisms operating synergistically to remove the pollutants in wastewaters. It offers the possibility of anodic oxidation and in situ generation of active adsorbents (such as hydrous ferric oxides, hydroxides of aluminum). At the same time cathodic reactions occur and the evolution of hydrogen gas is involved, causing flotation of the adsorbents. Good reviews of electrocoagulation were given by Chen [22], Mollah et al. [23] and Holt et al. [24]. In the electrocoagulation cell, the electrochemical reactions with metal Al as electrodes are

* Corresponding author. Tel.: +886 6 2674567/850; fax: +886 6 2675049.
E-mail address: ctwwang@mail.hwai.edu.tw (C.-T. Wang).

as follows: At Al anode



At the cathode



The Al^{3+} ions generated immediately hydrolyze to produce corresponding hydroxides and/or polyhydroxides in adequate pH. The Al hydroxides and polyhydroxides from the electrochemical dissolution were reported to have stronger affinity to capture the pollutants in the wastewater, causing more coagulation than those from the conventional Al coagulants. Additionally, the gas bubbles that evolve due to the water electrolysis can cause flotation of the pollutants and the coagulated materials. Therefore, electroflotation may also play an important part in an electrocoagulation cell. Although the $\text{Al}(\text{OH})_3$ produced by the anodic Al dissolution is thought more active to coagulate the pollutants in wastewater, the passivation of Al anodes and impermeable film formed on cathodes may interfere with the performance of electrocoagulation and electroflotation [24]. The formation of an inhibiting layer on the Al electrode surface prevents Al dissolution and electron transfer, limiting Al^{3+} to the solution. As a result, the electrocoagulation system is usually designed to operate in a condition of high voltage, usually higher than 10 V, to break down the inhibiting layer. The energy consumption is thus high and the electrodes are likely to be destroyed when using a high voltage for the long-term operation. In order to overcome these disadvantages, Kovatcheva and Parlapanski [25] used a low-frequency sonic field (40–200 Hz) to improve the performance of the electrocoagulation cell with carbon steel electrodes. They indicated that the quantity of iron hydroxide increased and hence the coagulation of SO_4^{-} and Cl^{-} was enhanced.

The purpose of this work is to investigate the removal efficiency of COD in the treatment of simulated laundry wastewater in an electrocoagulation/electroflotation cell. The effect of the operating variables, including the application of ultrasound, the applied voltage, the Cl^{-} concentration, the different types of electrode connection, the number of the electrodes and the different electrode material, on the removal efficiency of COD in the solution were examined. The energy efficiency of COD removal for the electrocoagulation cell was also calculated in this work.

2. Experimental

The schematic experimental setup is shown in Fig. 1. The monopolar electrocoagulation unit consisted of a 1-dm³ electrochemical reactor with three Al anodes and three Al cathodes. Each electrode was 40 mm × 30 mm. The total surface area of the anode and the cathode was 72 cm². The distance between electrodes was 10 mm. The electrochemical cell was placed inside an ultrasonic cleaning bath with a frequency 43 kHz and power of 80 W from Delta, model DC400H. The applied voltage was kept constant by means of a power supply (GW, GPR-25H30D). All the chemicals used in the experiments were of reagent grade. The Al electrodes were polished using grinding papers to remove the thin aluminum oxide film, and then rinsed with soap water and deionized water before electrolysis. The COD of the wastewater was measured by a Hach spectrophotometer (DR2500) and a Hach COD reactor. The agitation speed was 200 rpm. This speed allowed the chemical precipitate to grow large enough for removal [11,26]. The temperature and solution pH were not controlled, but were monitored using the ultrameter II from Myron L Company in the electrolysis. The initial pH of the laundry wastewater was 7.5.

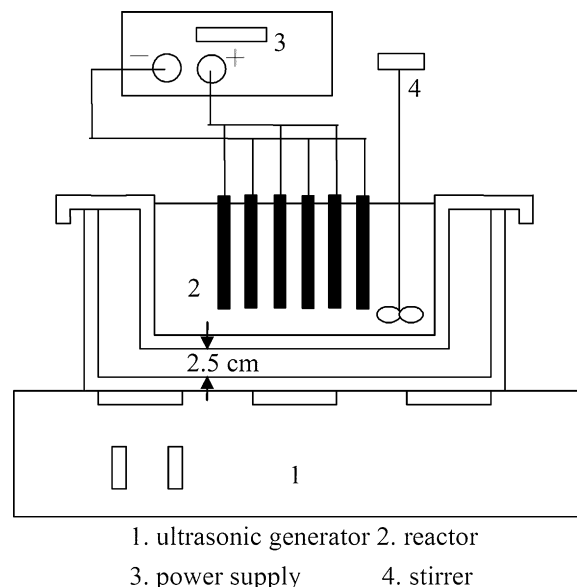


Fig. 1. The schematic experimental setup in this study.

The artificially simulated laundry wastewater was prepared by diluting concentrated liquid detergent produced by the Kao Corporation in Taiwan. The major composition in the detergent is LAS. The initial COD of the wastewater was 226 mg dm⁻³. The removal efficiency was defined as follows:

$$\text{removal efficiency (\%)} = \frac{\text{COD}_0 - \text{COD}}{\text{COD}_0} \times 100 \quad (4)$$

where COD_0 is the initial COD of the laundry wastewater.

3. Results and discussion

3.1. Effect of the application of ultrasound

The effects of ultrasound waves on the electrochemical systems are as follows [24–29]:

1. An improvement of hydrodynamics to increase mass transfer of species.
2. A cleaning and reactivating effect on an electrode surface to continuously regenerate a new surface, probably due to the effects of cavitations and/or microstreaming.
3. The alteration of kinetics and adsorption behavior on an electrode surface.

In addition, the application of high power ultrasound in wastewater treatment can destroy pollutants through a mechanism of producing free radicals with high oxidation power according to [30]:



The hydroxyl free radicals are strong oxidants, having the ability to destroy many organic and inorganic species. Therefore the application of ultrasound on an electrocoagulation cell may have dual effects (dissolution enhancement and sonolysis) on the removal of pollutants. However, at present our knowledge of the application of ultrasound on the electrocoagulation cell is still limited. Fig. 2 depicts the results of the change of COD with and without the application of ultrasound on the electrocoagulation cell in this study. As expected, the COD decreased rapidly at the beginning stage,

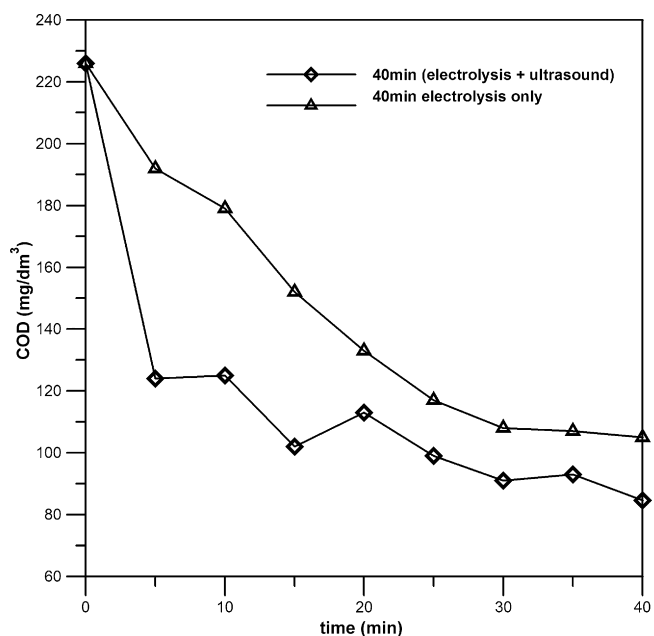


Fig. 2. Comparison of the typical change of COD with time in the absence and presence of ultrasound; applied voltage: 5 V.

then slowly and finally leveled out after 30-min electrolysis in the case without ultrasound. The ultimate removal efficiency of COD was maintained at about 54%. However, the COD in the solution decreased continuously during electrolysis in the case with ultrasound, reaching to about 62% after 40 min. The removal efficiency at different times is listed in Table 1. The significant difference is probably due to the regeneration of new electrode surface by cavitations and/or micro-streaming effect when applying ultrasound. The application of ultrasound on the electrocoagulation cell may not only enhance the dissolution rate of Al anodes, but also prevent the coverage of the gas bubbles on the electrodes, and thus enhance flotation of the pollutants. The effects of the gas bubbles include the stirring of the solution and their obstruction of the corresponding current by applying the constant-voltage mode. The hydrogen and oxygen bubbles attached to or located near the electrodes and the polymeric films on the electrodes likewise have ohmic resistance between the electrodes in the electrocoagulation cell [22]. The resistance was probably reduced because the detachment rate of the bubbles produced at the electrodes was enhanced and those films were partially destroyed due to the application of ultrasound. In addition, the solution temperature increased more rapidly when applying ultrasound in the electrocoagulation cell. According to the above results, the initial current at a constant voltage of 5 V increased from 0.244 A to 0.267 A when applying ultrasound in this work. The phenomena probably indicated that more electrochemical reactions occurred at the electrode surfaces. Therefore, we could observe that more colloids generated from the dissolution of Al anodes and suspended in the solution and more bubbles generated due to the electrolysis of water flowed upwards during the

Table 1
The removal efficiency of COD at different times

Time (min)	Removal efficiency (%)	
	Without ultrasound	With ultrasound
10	20.8	44.7
20	41.2	50.0
30	52.2	59.7
40	53.5	62.1

experimental runs when applying ultrasound in the electrocoagulation cell. Furthermore, it is seen that the curve of COD changed in the case with ultrasound slightly fluctuated after 5 min. This may be because the ultrasound has some negative effects on the Al hydroxide colloids. The most important effect is that a part of the pollutants adsorbed on the Al hydroxide colloids can desorb and return to the solution with the application of ultrasound [31,32]. Despite this negative effect when ultrasound was applied in the electrocoagulation cell, the COD still decreased with time. This continuous reduction in COD showed that the application of ultrasound could enhance the removal of COD in this work due to the enhanced electroflotation and electrocoagulation.

3.2. Change in the characteristics of the solution

The change in the electric conductivity of the solution, total dissolved solids (TDS), and temperature along with the electrolysis time in this study are shown in Fig. 3. The solution temperature increased steadily from 28.3 °C to 35.5 °C during 40-min electrolysis, due to the input of both electrical energy and sonic energy. The solution conductivity decreased from the original 334 $\mu\text{S cm}^{-1}$ to 229 $\mu\text{S cm}^{-1}$ and the TDS from 214 mg dm^{-3} to 147 mg dm^{-3} , indicating some species in the wastewater were removed by the electrocoagulation/electroflotation. Because the pH was only monitored and not controlled in this study, it will change during the electrolysis. Fig. 4 shows the pH change of the solution along with the electrolysis time. It is obvious that different trends were found in the acidic, neutral, and basic solution. In the strongly acidic solution (initial pH 2.1), the solution pH increased slowly in the initial phase, approached 4, and then leveled out. In the weakly acidic solution, the pH was raised from the initial pH of 5.1–6.9. The change of solution pH in both cases was about 1.8 of a pH unit after 40-min electrolysis. When the solution was nearly neutral (initial pH 7.5), only a small pH change was observed. Contrary to the pH increase in the acidic solution, a decrease of pH occurred from the initial pH of 9.5–8.2 in the basic solution. Consequently, the solution pH slowly approached a more neutral pH in all cases. Thus, the neutralization of pH can be thought of as a feature of the electrocoagulation cell, which is consistent with the result, found by Hu et al. [9].

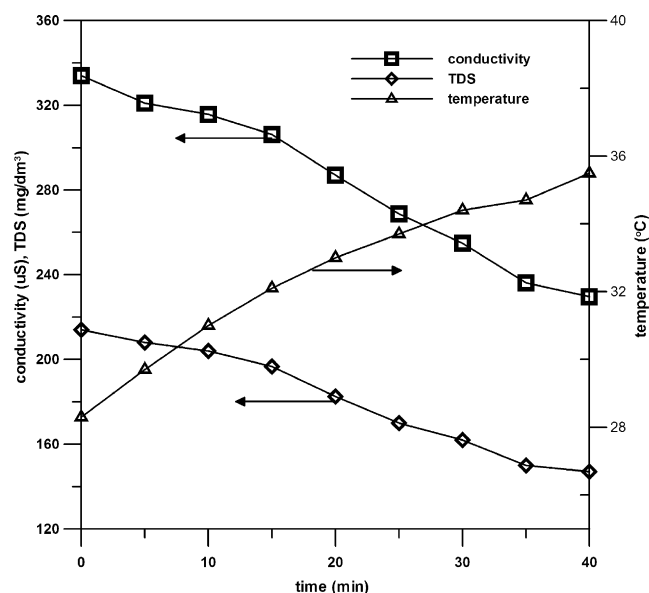


Fig. 3. Typical change of the electric conductivity, TDS, temperature with time; applied voltage: 5 V.

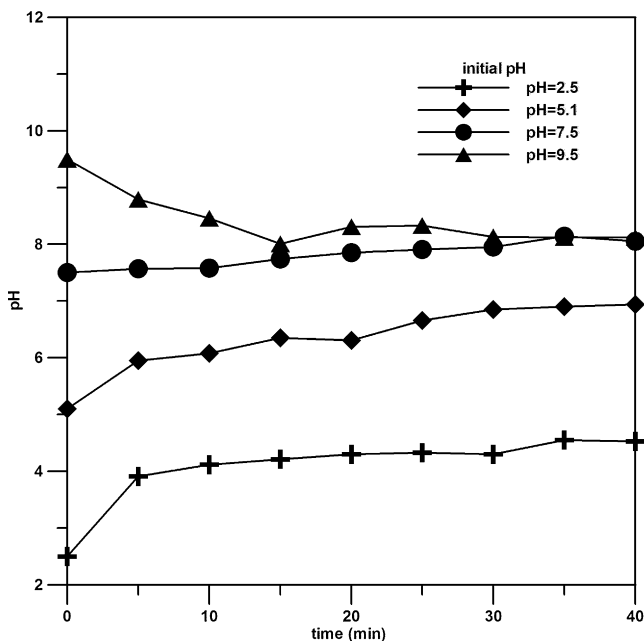


Fig. 4. Neutralization effect of the electrocoagulation/electroflotation process.

3.3. Effect of the applied voltage

One of the most important parameters that can affect the removal or destruction efficiency in the electrochemical process is the applied current or the voltage. In this study we employed the current–voltage mode; therefore the effect of the applied voltage on the COD removal efficiency should be investigated, as depicted in Fig. 5. The COD removal efficiency was very low (0.2%) when only the sonolysis was used in this work, though ultrasound was reported to have an effect on the wastewater treatment in AOP processes [30]. The possible reason was that the power of the ultrasound cleaning bath used in this experimental, 80 W, was not

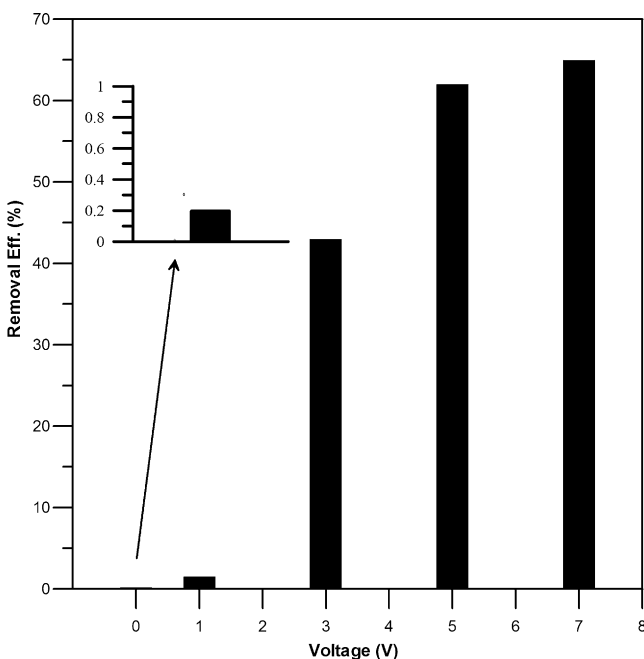


Fig. 5. Effect of the applied voltage on the removal efficiency of COD.

enough to produce sufficient hydroxyl free radicals to destroy the pollutants according to Eq. (4) or to produce the Al^{3+} via the following simple dissolution reaction of the metal Al plate [33–35].



It can be seen from Fig. 5 that the removal efficiency of COD was raised with the application of voltage on the reactor. The removal efficiency of COD from the laundry wastewater was still low, only 1.8% when applying 1 V on the Al anodes. When the applied voltage was raised to 3 V, the removal efficiency rose dramatically to about 43% because a larger amount of Al^{3+} was produced via anodic metal dissolution, causing coagulation, and more bubbles formed at the cathode, causing flotation. Although the removal efficiency of COD increased to 62% and 65% with increasing the applied voltage to 5 V and 7 V, the optimal applied voltage was 5 V due to this study's concern with the energy consumption.

3.4. Effect of initial solution pH

In the electrocoagulation/electroflotation process, pH of the solution is known to play an important role in the removal efficiency of pollutants [6]. To examine the effect of pH on COD removal for laundry wastewater, we adjust the initial solution pH to a desired value, ranging from 2.5 to 9.5, by adding diluted $\text{NaOH}_{(\text{aq})}$ and $\text{H}_2\text{SO}_{4(\text{aq})}$ to the solution. Fig. 6 demonstrates the removal efficiency of COD at different initial values of pH. The removal efficiencies were about 30%, 49%, 66%, 62%, 63% and 54% at pH of 2.5, 3.1, 5.1, 7.5, 9.5 and 11.8, respectively. The optimal initial pH of this study was found to be 5.1. The removal efficiency was low and significantly decreased with decreasing pH when $\text{pH} < 5.1$. The possible explanation of this phenomenon was given from the observation of the solubility diagram of aluminum hydroxide [6], which shows that the extent of hydrolysis of Al^{3+} depends on the pH. At a low pH, Al^{3+} is favored in the solution and thus the coagulation effect was insignificant, resulting in low removal efficiency of COD. The hydrolysis and polymerization of Al^{3+} at a pH range of 5–9 forms mononuclear and/or polynuclear aluminum complexes, e.g. $\text{Al}(\text{OH})_3$, $\text{Al}(\text{OH})_2^+$, $\text{Al}_2(\text{OH})_4^+$, and $\text{Al}_{17}(\text{OH})_{32}^{7+}$, which are effective coagulants for the pollutants. But at high solution pH, the domi-

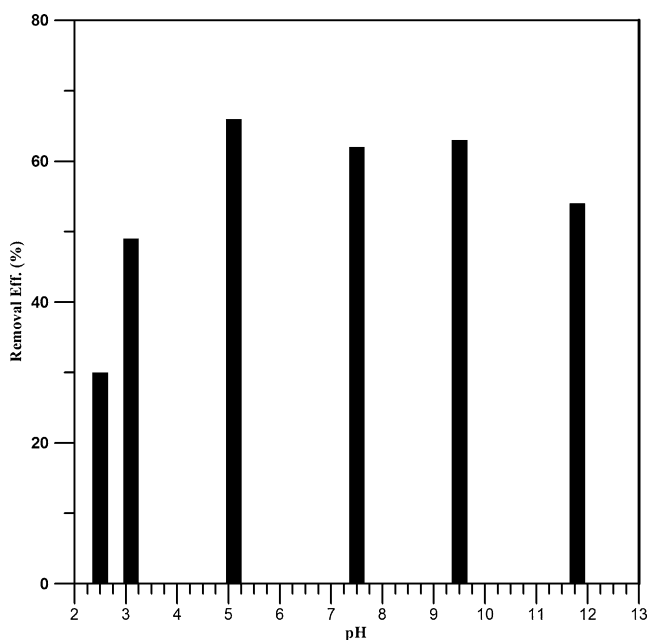


Fig. 6. Effect of the initial pH of the solution on the removal efficiency of COD.

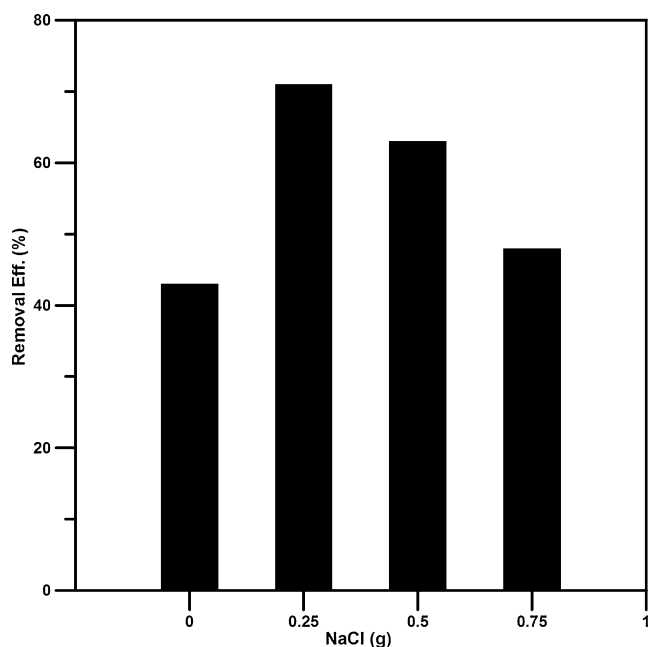


Fig. 7. Effect of the Cl^- addition on the removal efficiency of COD; applied voltage: 3 V.

nant species is $\text{Al}(\text{OH})_4^-$, which obviously does not coagulate the pollutants [6].

3.5. Effect of Cl^- addition

The problem of electrode passivation is a serious shortcoming in the current application of electrocoagulation. To destroy the passivation layer and hence enhance the dissolution rate of Al or Fe electrodes is thus crucial. In addition to the application of ultrasound to the electrolytic cell, the addition of Cl^- to acidic and neutral solutions was reported to increase the anodic dissolution rate of Al, either by the incorporation of Cl^- to the oxide film or by the participation of Cl^- in the metal dissolution reaction [36]. Fig. 7 shows the effect of addition of Cl^- ions into the solution on the removal efficiency of COD. The voltage applied was 3 V. The removal efficiency was greatly enhanced by adding 0.25 g NaCl to the solution, obtaining removal efficiency of 71%. The above removal efficiency was greater than that of the case of applying 7 V without adding NaCl. Hence, adding NaCl to the wastewater is probably a better choice for increasing the performance of the electrocoagulation technology. However, the removal efficiency decreased when more NaCl was added to the solution. This demonstrated an excess amount of Cl^- in the solution was detrimental to the coagulation of the pollutants. The likely explanation is that the Cl^- ions in the solution containing $\text{Al}(\text{OH})_3$ will form some transitory compounds, such as $\text{Al}(\text{OH})_2\text{Cl}$, $\text{Al}(\text{OH})\text{Cl}_2$, and AlCl_3 . The transitory compounds will be finally dissolved in the solution with excess Cl^- , as a form of AlCl_4^- [36]. Thus, the amount of $\text{Al}(\text{OH})_3$ coagulants decreased, resulting in the decrease

of the removal efficiency. In addition to the coagulation process, an indirect electrochemical oxidation likely occurs if the solution contains Cl^- . The Cl^- will be discharged at the anode to generate Cl_2 , which will be immediately dissolved in the solution, chemically converted to ClO^- . The ClO^- can oxidize the pollutants effectively. Therefore the removal efficiency of COD will increase.

3.6. Effect of the electrode connection and the number of electrodes

Two different types of electrode connection in an electrocoagulation cell were used in the literature [23]. The monopolar electrodes have a characteristic of a low voltage and a high current, while on the other hand the bipolar electrodes have a high voltage and a lower current. For comparing the removal efficiency of these two different types of electrode connections, the middle four electrodes were disconnected from the power supplier, forming a bipolar electrode connection in an experimental run. The result is shown in Table 2. The removal efficiency was about 62% and 7% for monopolar electrodes and bipolar electrodes, respectively. It was obviously concluded that the monopolar electrodes were superior to the bipolar electrodes.

Table 2 also lists the removal efficiency of COD by using different numbers of electrodes, operating in the constant-voltage mode, in the electrocoagulation cell. Although the removal efficiency increased with increasing the numbers of electrodes, the difference was not so significant, and the removal efficiency of COD increased merely from 51.3% to 62%. Therefore the use of more electrodes connected in parallel was not as effective as we expected. From the observation on the Al plate anode, we can find that the corrosion of each Al electrode was more severe when using two plates of Al electrodes. This explained that more dissolution of Al anode was achieved in the electrolysis. Therefore we must change the electrodes of the electrocoagulation cell at shorter intervals when fewer electrodes are employed.

3.7. Electricity, energy consumption, and energy efficiency

The energy consumed in the electrocoagulation of the laundry wastewater using a constant voltage was calculated by the equation:

$$E = \int I \times V dt = V \int I dt = V \times I_{\text{avg}} \times \Delta t = V \times Q \quad (7)$$

where V is the applied voltage, I the total current, I_{avg} the average total current, Δt the electrocoagulation time, Q the electricity. The electricity and the electric energy consumption in the 40-min electrocoagulation and energy efficiency (COD removal per joule) are shown in Table 2. The energy efficiency was $267.0 \text{ mg dm}^{-3} \text{ kW h}^{-1}$, $404.8 \text{ mg dm}^{-3} \text{ kW h}^{-1}$, and $999.0 \text{ mg dm}^{-3} \text{ kW h}^{-1}$ for six, four, and two plates of electrodes, respectively. The energy consumed increased, but the energy efficiency decreased with increasing the number of electrodes. For comparing the removal efficiency of COD with Al and Fe anode, Fe plates with the same surface area were used in this study. The result is also listed in Table 2. The removal

Table 2
Effect of the electrode connection, the number of electrodes and the electrode material

	Al (six plates) Monopolar	Al (four plates) Monopolar	Al (two plates) Monopolar	Al (six plates) Bipolar	Fe (six plates) Monopolar
Removal eff. (%)	62	54	51.3	7	53
Energy consumed ($\times 10^{-4} \text{ kWh}$)	3.82	2.89	1.81	3.23	3.53
COD removal (mg dm^{-3})(kWh^{-1})	267.0	404.8	999.0	43.3	266.3

efficiency of using Al electrodes was higher than that of using Fe electrodes in the treatment of laundry wastewater.

4. Conclusions

In this study, the electrocoagulation/electroflotation process was applied for removing the COD of simulated laundry wastewater. The following results were obtained:

1. The application of ultrasound to the electrocoagulation cell can increase the removal efficiency of COD in the laundry wastewater due to the increasing electroflotation and electrocoagulation.
2. The pH approached to neutrality in all cases. Therefore, the electrocoagulation technology cannot only remove the pollutants in the wastewater but also act as a pH neutralizer.
3. Although the removal efficiency increased with increasing applied voltage, the optimal applied voltage was 5 V in this work when considering the removal efficiency and the energy consumption simultaneously.
4. The addition of some Cl^- to the wastewater increased the removal efficiency of COD. But excess Cl^- in the solution can transform the $\text{Al}(\text{OH})_3$ into AlCl_4^- and thus decrease the removal efficiency.
5. The performance of the monopolar connection of electrodes was better than that of the bipolar connection.
6. The removal efficiency of using Al electrodes was higher than that of using Fe electrodes in the treatment of laundry wastewater.
7. The highest COD removal per joule was $999 \text{ mg dm}^{-3} \text{ kW h}^{-1}$.

References

- [1] D. Rajkumar, K. Palanivelu, Electrochemical treatment of industrial wastewater, *J. Hazard. Mater. B* 113 (2004) 123–129.
- [2] C.T. Wang, Decolorization of congo red with three-dimensional flow-by packed-bed electrodes, *J. Environ. Sci. Health A* 38 (2003) 399–413.
- [3] E. Brillas, J.C. Calpe, J. Casado, Mineralization of 2,4-D by advanced electrochemical oxidation processes, *Water Res.* 34 (2000) 2253–2262.
- [4] H.G. Leu, S.H. Lin, T.M. Lin, Enhanced electrochemical oxidation of anionic surfactants, *J. Environ. Sci. Health A* 33 (1998) 681–699.
- [5] G. Lissen, J. Pieters, M. Verhaege, L. Pinoy, W. Verstraete, Electrochemical degradation of surfactants by intermediates of water discharge at carbon-based electrodes, *Electrochim. Acta* 48 (2003) 1655–1663.
- [6] P.K. Holt, G.W. Barton, M. Wark, C.A. Mitchell, A quantitative comparison between chemical dosing and electrocoagulation, *Colloids Surf. A* 221 (2002) 223–248.
- [7] L.M. Balmer, A.W. Foulds, Separation oil from oil-in water emulsions by electroflocculation/electroflotation, *Filtr. Sep.* 23 (1986) 366–369.
- [8] X. Chen, G. Chen, P.L. Yue, Separation of pollutants from restaurant wastewater by electrocoagulation, *Sep. Purif. Technol.* 19 (2000) 65–76.
- [9] C.Y. Hu, S.L. Lo, W.H. Kuan, Effects of co-existing anions on fluoride removal in electrocoagulation (EC) process using aluminum electrodes, *Water Res.* 37 (2003) 4513–4523.
- [10] P.R. Kumar, S. Chaudhari, K.C. Khilar, S.P. Mahajan, Removal of arsenic from water by electrocoagulation, *Chemosphere* 55 (2004) 1245–1252.
- [11] J.S. Do, M.L. Chen, Decolorization of dye-containing solutions by electrocoagulation, *J. Appl. Electrochem.* 24 (1994) 785–790.
- [12] T.H. Kim, C. Park, E.B. Shin, S. Kim, Decolorization of disperse and reactive dyes by continuous electrocoagulation process, *Desalination* 150 (2002) 165–175.
- [13] M. Kobya, O.T. Can, M. Bayramoglu, Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes, *J. Hazard. Mater. B* 100 (2003) 163–178.
- [14] N. Daneshvar, H. Ashassi-Sorkhabi, A. Tizpar, Decolorization of orange II by electrocoagulation method, *Sep. Purif. Technol.* 31 (2003) 153–162.
- [15] N. Daneshvar, H. Ashassi-Sorkhabi, M.B. Kasiri, Decolorization of dye solution containing Acid Red 14 by electrocoagulation with a comparative investigation of different electrode connections, *J. Hazard. Mater. B* 112 (2004) 55–62.
- [16] Z. Zaroual, M. Azzi, N. Saib, E. Chainet, Contribution to the study of electrocoagulation mechanism in basic textile effluent, *J. Hazard. Mater. B* 131 (2006) 73–78.
- [17] O. Larue, E. Vorobiev, C.V.B. Durand, Electrocoagulation and coagulation by iron of latex particles in aqueous suspensions, *Sep. Purif. Technol.* 31 (2003) 177–192.
- [18] J. Ge, J. Qu, P. Lei, H. Liu, New bipolar electrocoagulation–electroflotation process for the treatment of laundry wastewater, *Sep. Purif. Technol.* 36 (2004) 33–39.
- [19] P. Gao, X. Chen, F. Shen, G. Chen, Removal of chromium(VI) from wastewater by combined electrocoagulation–electroflotation without a filter, *Sep. Purif. Technol.* 38 (2005) 117–123.
- [20] Ş. İrdemez, N. Demircioğlu, Y.Ş. Yıldız, Z. Bingül, The effects of current density and phosphate concentration on phosphate removal from wastewater by electrocoagulation using aluminum and iron plate electrodes, *Sep. Purif. Technol.* 52 (2006) 218–223.
- [21] Ş. İrdemez, Y.Ş. Yıldız, V. Tosunoğlu, Optimization of phosphate removal from wastewater by electrocoagulation with aluminum plate electrodes, *Sep. Purif. Technol.* 52 (2006) 394–401.
- [22] G. Chen, Electrochemical technologies in wastewater treatment, *Sep. Purif. Technol.* 38 (2004) 11–41.
- [23] M.Y.A. Mollah, P. Morkovsky, J.A.G. Gomes, M. Kesmez, J. Porga, D.L. Cocke, Fundamentals, present and future perspectives of electrocoagulation, *J. Hazard. Mater. B* 114 (2004) 199–210.
- [24] P.K. Holt, G.W. Barton, C.A. Mitchell, The future for electrocoagulation as a localized water treatment technology, *Chemosphere* 59 (2005) 355–367.
- [25] V.K. Kovatcheva, M.D. Parlapaniski, Sono-electrocoagulation of iron hydroxides, *Colloids Surf. A* 149 (1999) 603–608.
- [26] N. Adhoum, L. Monser, Decolourization and removal of phenolic compounds from olive mill wastewater by electrocoagulation, *Chem. Eng. Process* 43 (2004) 1281–1287.
- [27] B. Pollet, J.P. Lorimer, J.Y. Hihn, F. Touyeras, T.J. Mason, D.J. Walton, Electrochemical study of silver thiosulphate reduction in the absence and presence of ultrasound, *Ultrason. Sonochem.* 12 (2005) 7–11.
- [28] B. Pollet, J.P. Lorimer, S.S. Phull, J.Y. Hihn, Sono-electrochemical recovery of silver from photographic processing solutions, *Ultrason. Sonochem.* 7 (2000) 69–76.
- [29] M.L. Doche, J.Y. Hihn, A. Mandroyan, R. Viennet, F. Touyeras, Influence of ultrasound power and frequency upon corrosion kinetics of zinc in saline media, *Ultrason. Sonochem.* 10 (2003) 357–362.
- [30] Y.G. Adewuyi, Sonochemistry: environmental science and engineering applications, *Ind. Eng. Chem. Res.* 40 (2001) 4681–4715.
- [31] N.H. Ince, G. Tezcanli, R.K. Belen, I.G. Apikyan, Ultrasound as a catalyzer of aqueous reaction systems: the state of the art and environmental applications, *Appl. Catal. B* 29 (2001) 167–176.
- [32] R.S. Juang, S.H. Lin, C.H. Cheng, Liquid-phase adsorption and desorption of phenol onto activated carbons with ultrasound, *Ultrason. Sonochem.* 13 (2006) 251–260.
- [33] T. Picard, G. Cathalifaud-Feuillade, M. Mazet, C. Vandesteendam, Cathodic dissolution in the electrocoagulation process using aluminum electrodes, *J. Environ. Monit.* 2 (2002) 77–80.
- [34] J. Kang, Y. Shin, Y. Tak, Growth of etch pits formed during sono-electrochemical etching of aluminum, *Electrochim. Acta* 51 (2005) 1012–1016.
- [35] P. Diodati, G. Giannini, Cavitation damage on metallic plate surfaces oscillating at 20 kHz, *Ultrason. Sonochem.* 8 (2001) 49.
- [36] W.J. Lee, S.I. Pyun, Effects of hydroxide ion addition on anodic dissolution of pure aluminum in chloride ion-containing solution, *Electrochim. Acta* 44 (1999) 4041–4049.