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Separation of pollutants from restaurant wastewater by electrocoagulation

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Abstract

The characteristics of restaurant wastewater were investigated. High oil and grease contents were detected. Electrocoagulation was used to treat this type of wastewater. Different electrode materials and operational conditions were examined. Aluminum was preferred to iron. Charge loading was found to be the only variable that affected the treatment efficiency significantly. The optimum charge loading and current density were 1.67–9.95 F/m^3 wastewater and 30–80 A/m^2 depending on the wastewater tested. The removal efficiency of oil and grease exceeded 94% for all wastewaters tested. The experimental results also show that the electrocoagulation can neutralize wastewater pH. Several mechanisms associated with pH variation are proposed.

Keywords: Charge loading; Chemical oxygen demand; Current density; Oil and grease; Removal efficiency

1. Introduction

There are nearly 9000 restaurants and more than 200 fast-food shops in Hong Kong and they use over half a million tons of water everyday. The direct discharge of wastewater from these restaurants and shops down the drain is a huge extra burden to the municipal wastewater collection and treatment works. The oil and grease contained in the wastewater aggregate and foul the sewer system and generate an unpleasant odor. Basically, restaurant wastewater treatment facilities must be highly efficient in removing oil and grease, cause no food contamination, and be compact in size. Low capital and operating costs are important because profit margins of most restaurants are small. In addition, the technology has to be simple so that it can be operated easily either by a chef or a waiter. Conventional biological processes are therefore ruled out due to the requirement of large space and skilled technicians. Chemical coagulation/settlement is not practicable because of the low efficiency in removing light and finely dispersed oil particles and possible contamination of foods by chemicals. The G-bag approach, which used a bag of adsorbent to capture the pollutants and degrade the pollutants with the immobilized microorganisms on the ad-

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sorbent, seems to be a good alternative only if the system can be designed simple and free from fouling.

Electrocoagulation is a simple and efficient method for the treatment of many water and wastewaters. It has been tested successfully to treat potable water [1,2], textile wastewater [3–5], tar sand and oil shale wastewater [6], carpet wastewater [7], urban wastewater [8], chemical fiber wastewater [9] and oil–water emulsion [10]. It has also been used to remove clay suspensions [11], bentonite [12], and dye stuff [13–15] from wastewaters. This process is characterized by a fast rate of pollutant removal, compact size of the equipment, simplicity in operation, and low capital and operating costs. Moreover, it is particularly more effective in treating wastewaters containing small and light suspended particles, such as oily restaurant wastewater, because of the accompanying electro-flotation effect. Hence, it is expected that the electrocoagulation would be an ideal choice for treating restaurant wastewaters. There are, however, no reported data in literature. The objective of the present study is to examine the feasibility of electrocoagulation in treating restaurant wastewater and to determine the optimum operational conditions.

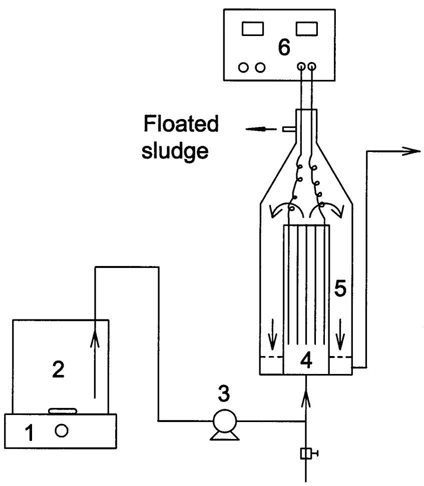

Fig. 1. Schematic diagram of experimental set-up. (1) magnetic stirrer; (2) feed sludge tank; (3) pump; (4) electrochemical reactor; (5) separator; (6) DC power supply.

2. Experimental

The experimental setup is schematically shown in Fig. 1. The electrocoagulation unit consists of an electrochemical reactor and a separator. The volumes of the reactor and sludge separator are 0.30 and 1.2 l, respectively. Wastewater flows upward in the electrochemical reactor and downward in the separator. It was designed to achieve easy separation of oil and grease from the wastewater. There are five electrodes connected in a dipolar mode in the electrochemical reactor, each with a dimension of $140 \times 44 \times 3$ mm. The effective area of each electrode is 56 cm^2 and the spacing between electrodes is 6 mm. A stirrer was employed in the feed tank to maintain an unchanged composition of the feeding wastewater.

The wastewater collected from a student canteen in the Hong Kong University of Science and Technology (HKUST) was used for all experiments regarding the selection of electrode materials and the effects of operating parameters on treatment efficiency. Wastewaters from both Chinese and Western restaurants were tested using the optimal operating condition. Wastewater was fed to the reactor 15 min after the start of the stirrer. Effluent from the electrocoagulation unit was sampled only after steady state operation was achieved. Samples were allowed to settle for 1.5 h in a 2 l beaker before any analysis was made.

Chemical oxygen demand (COD) was measured using COD reactor and direct reading spectrophotometer (DR/2000, HACH, USA). Oil and grease were first extracted with petroleum ether at pH below 2, then examined using UV Spectrophotometer (UV-1206 UV–Vis spectrophotometer, Shimadzu, Japan) at 210 nm. Peanut oil was used as calibration standard because it is the most common food oil in Hong Kong. Biological oxygen demand (BOD_5), suspended solids (SS), pH, and conductivity were examined following standard methods [16].

Table 1
Characteristics of restaurant wastewater

Restaurant	Chinese restaurant	Western restaurant	American fast-food	Student canteen	UC bistro	Permission standards in H.K.
Number of samples	10	10	11	14	3	–
PH	6.62–7.96	6.94–9.47	6.30–7.23	6.82–8.76	6.03–8.22	6–10
COD (mg/l)	292–3390	912–3500	980–4240	900–3250	1500–1760	3000
BOD_5 (mg/l)	58–1430	489–1410	405–2240	545–1630	451–704	1200
Oil and grease (mg/l)	120–172	52.6–2100	158–799	415–1970	140–410	100
SS (mg/l)	13.2–246	152–545	68–345	124–1320	359–567	1200
Conductivity (μS/cm)	227–661	261–452	254–706	233–1570	341–514	–

3. Results and discussion

3.1. Characteristics of restaurant wastewater

Restaurant wastewater is water that has been used for cleaning meats and vegetables, washing dishes and cooking utensils, or cleaning the floor. Due to the difference among different cuisines, the wastewater composition of Chinese restaurant is expected to be different from that of Western restaurant. Since the food served for breakfast, lunch and dinner are different, the wastewater composition would vary from time-to-time for a particular restaurant. Thus, it is very difficult to have one meaningful characterization for each restaurant. To make matters worse, there is no collection system available. Thus, waste samples have to be scooped from the entrance of the drains at representative time. A total of 48 samples were collected from five restaurants in HKUST for the characterization purpose. The results are listed in Table 1. As expected the oil and grease content was very high. The pollutant concentration varied in a wide range so did the conductivity. It is interesting to note that the highest COD, oil and grease values were found from wastewater discharged by an American fast-food restaurant and a Western restaurant, respectively. The highest suspended solid content was found from student canteen serving Chinese as well as Western fast foods. However, it should be pointed out that the pollutant concentration variations are comparable for all the restaurants. In comparison with the permission standards for effluents discharged into foul sewers leading into the Hong Kong Government sewage treatment plants, the only parameter that consistently exceeds the standard is the oil and grease content although COD and BOD_5 sometimes are also a bit too high.

3.2. Selection of electrode materials

Electrode assembly is the heart of the present treatment facility. Therefore, the appropriate selection of its materials is very important. The most common electrode materials for electrocoagulation are aluminum and iron. They are cheap, readily available, and proven effective. Thus both were tested in this study. To save analytical effort and time, only COD, oil and grease content were determined for this series of samples. Fig. 2 compares the treatment efficiency for these two kinds of electrodes under the same charge loading. It is clear that both materials are equally effective. Over 90% of the pollutants were removed from the wastewater with an initial oil and grease concentration as high as 1500 mg/l. The detailed discussion of this aspect will be given subsequently.

The effluent with aluminum electrodes was found very clear and stable, whereas the effluent with iron electrodes appeared greenish first, and then turned yellow and turbid. The green and yellow colors must have resulted from Fe(II) and Fe(III). Fe(II) is the common ion generated in situ of electrolysis of iron. It has relatively high solubility at acidic or neutral conditions and can be oxidized easily into Fe(III) by dissolved oxygen in water. Fe(III) exists in yellow fine particles of $Fe(OH)_3$ and is difficult to settle. In addition, electrode corrosion at open circuit was found for iron. This creates problems for restaurant wastewater treatment because most restaurants do not open 24 h a day. Thus, it is obvious that aluminum is a better electrode material than iron for the present application. Consequently, all subsequent experiments were carried out with aluminum electrodes.

3.3. Effect of influent pH

It has been established that the influent pH is an important operating factor influencing the performance of electrochemical process [5,13,17]. To examine its effect, the wastewater was adjusted to the desired pH for each experiment by using sodium hydroxide or sulfuric acid. Fig. 3 demonstrates the removal efficiencies of COD, oil and grease as a function of the influent pH. Although the maximum removals of COD, oil and grease were observed at pH around 7, the pH effect is not very significant in the range 3–10. COD removal dropped dramatically at pH larger than 10. But fortunately, most raw restaurant wastewaters have pHs within the range 6–10. The drop of COD removal efficiency from over 90% in Fig. 2 to about 72% in Fig. 3 can be attributed to the different compositions of the two wastewater tested. The wastewater COD is from two sources, oil and grease as well as dissolved organic compounds. Electrocoagulation is effective in the removal of oil and grease, but not for the dissolved organic compound.

Fig. 4 shows the pH change of the wastewater after electrocoagulation. As observed by other investigators [1], a pH increase occurs when the influent pH is low. However, it is also found that when the influent pH is above 9, a pH drop occurs. In other words, the electrocoagulation can act as pH neutralization. This newly found characteristic of the electrocoagulation is quite meaningful in its application to wastewater treatment. As mentioned earlier, the typical pH range of

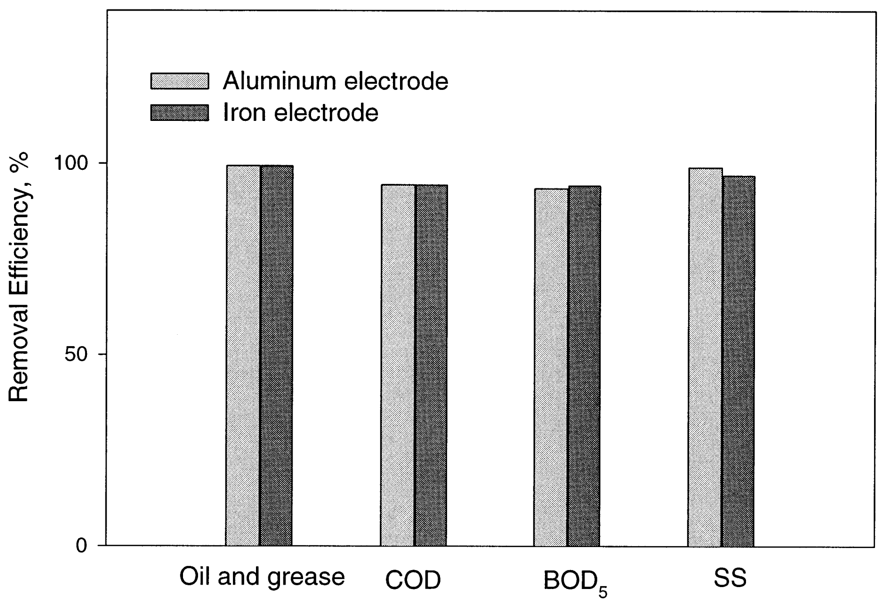

Fig. 2. Comparison of the treatment efficiency between aluminum electrode and iron electrode. Charge loading 4.97 F/m^3, feed flow rate 9.0 l/h, original pH 6.80, COD 2750 mg/l, BOD_5 825 mg/l, oil and grease 1500 mg/l, SS 574 mg/l, conductivity 476 μS/cm.

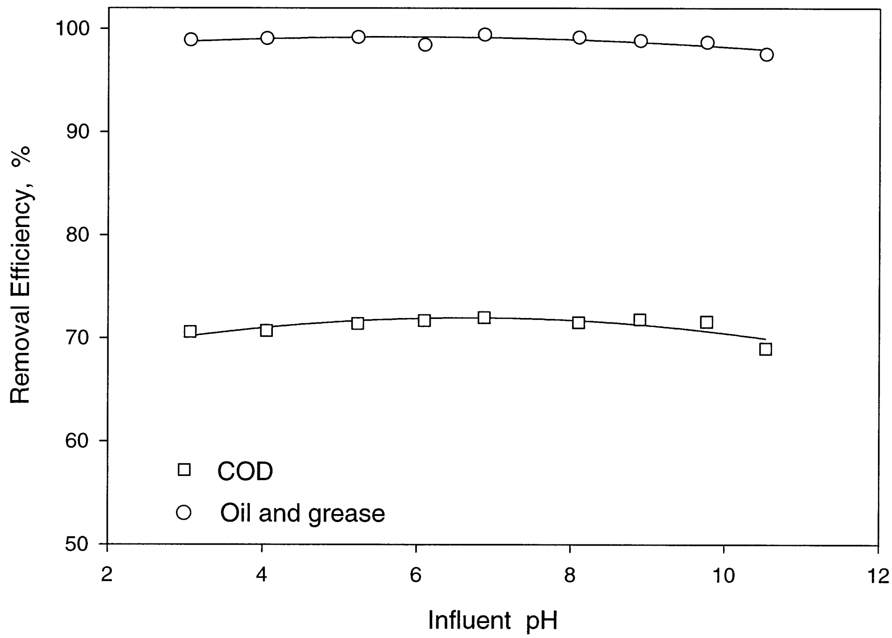

Fig. 3. Effect of influent pH on COD, oil and grease removal. Charge loading 6.63 F/m^3, feed flow rate 4.5 l/h, original COD 1010 mg/l, oil and grease 505 mg/l, conductivity 510 μS/cm.

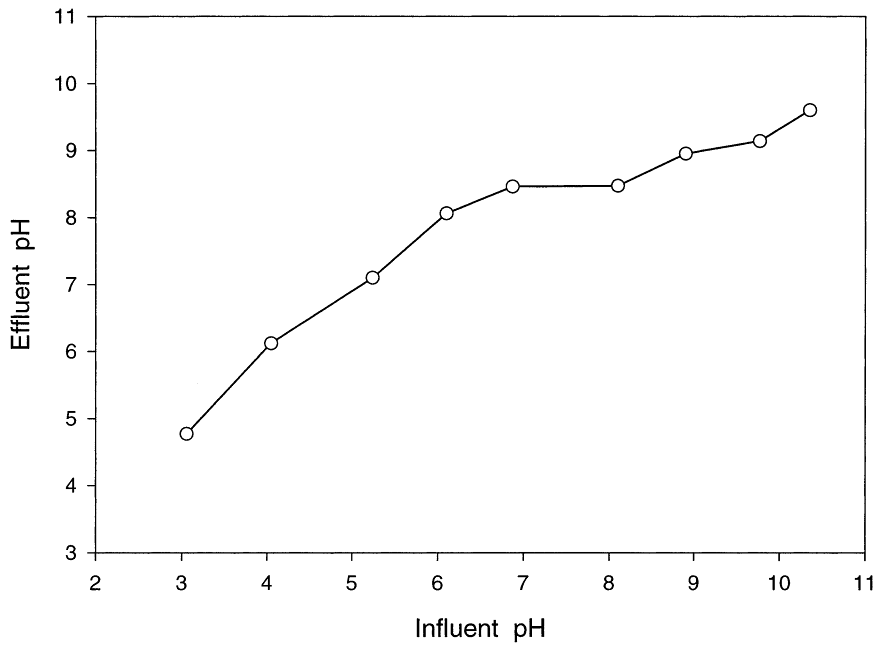

Fig. 4. pH change after electrocoagulation. Charge loading 6.63 F/m^3, feed flow rate 4.5 l/h, original COD 1010 mg/l, oil and grease 505 mg/l, conductivity 510 μS/cm.

restaurant wastewaters is from 6 to <10. For this range of influent pH, the effluent pH is in the range 6–9 as shown in Fig. 4, which allows the effluent to be directly discharged into foul sewers without further pH adjustment.

Vik et al. [1] attributed the pH increase to hydrogen evolution at cathodes. A complete examination of what happens in the electrocoagulation process shows that there are the following electrochemical and chemical reactions at anodes or in the bulk wastewater:

$$Al - 3e = Al^{3+} \quad (1)$$

$$Al^{3+} + 3H_2O = Al(OH)_3 + 3H^+ \quad (2)$$

$$2H_2O - 4e = O_2 + 4H^+ \quad (3)$$

$$2Cl^- - 2e = Cl_2 \quad (4)$$

$$Cl_2 + H_2O = HOCl + H^+ + Cl^- \quad (5)$$

$$HOCl = OCl^- + H^+ \quad (6)$$

As shown in Fig. 4, when the influent pH was in the range of 6.87–9.10, the effluent pH was 8.47–8.95. Under these pH conditions, Reactions (2); (5) and (6) are quite complete and thus the total amount of H^+ produced in the Reactions (2); (3); (5) and (6) was almost the same as that reduced in the hydrogen evolution. Actually, the pH change can be from a few mechanisms. One of them is the transfer of CO_2. At acidic condition, CO_2 is over saturated in wastewater and can release from wastewater owing to H_2 bubble disturbance, which causes a pH increase. In addition, some anions present in wastewater such as Cl^-, SO_4^{2-}, HCO_3^-, $HSiO_4^-$, NO_3^- etc. can exchange partly with OH^- in $Al(OH)_3$ to free OH^-, which also causes a pH increase. Moreover, if the influent is acidic, both Reactions (2) and (6) would shift towards the left hand side, which again results in an increase in pH. At high pH condition, Ca^{2+} and Mg^{2+} present in the wastewater can coprecipitate with $Al(OH)_3$ in the form of hydroxide, leading to a pH decrease. Furthermore, because $Al(OH)_3$ is a typical amphoteric metal hydroxide, Reaction (7) can take place at very high pH, leading to a pH decrease.

$$Al(OH)_3 + OH^- = Al(OH)_4^- \quad (7)$$

3.4. Effect of current density

Some investigators have reported that current density can influence the treatment efficiency of the electrochemical process [8]. This conclusion was made based on the experimental conditions where the charge loading was also changed. Therefore, it remains unclear whether the treatment efficiency was affected by current density or by charge loading. In the present study, the current density effect was investigated at the same charge loading by varying wastewater flow proportionally to the applied current. Since it has been shown in the previous section that pH did not affect the pollutant removal significantly, the pH value was not adjusted for all subsequent experiments. The result is shown in Fig. 5. Surprisingly, the current density almost had no effect on COD, oil and grease removals although it varied in a very large range from 12.50 to 108.9 A/m^2 at a fixed charge loading of 6.63 F/m^3. This indicates that it is not the current density but the charge loading that really affects the treatment efficiency.

Such a conclusion does not rule out the advantage of using high current density because the wastewater retention time decreases correspondingly. For example, when the current density was increased from 12.5 to 108.9 A/m^2, the retention time of the wastewater in the electrocoagulation unit was shortened from 60 to 6.5 min. This means that the electrocoagulation equipment can be almost 10 times smaller for current density at 108.9 A/m^2 than for that at 12.5 A/m^2. Of course, the electrolysis voltage and power requirement would increase with the increase of the current density as shown in Fig. 6. An increase in current density from 12.5 to 108.9 A/m^2 causes an increase in voltage between electrode from 1.33 to 6.08 V and an increase in power requirement from 0.25 to 1.07 kW h/m^3. Apparently, there exists an optimum current density for the lowest total cost of investment and operation. The exact range of this optimum current density depends on the geographical as well as economical situation where the electrocoagulation is applied. For the restaurant wastewater typically with a conductivity range of 227–1570 μS/cm, the optimal current

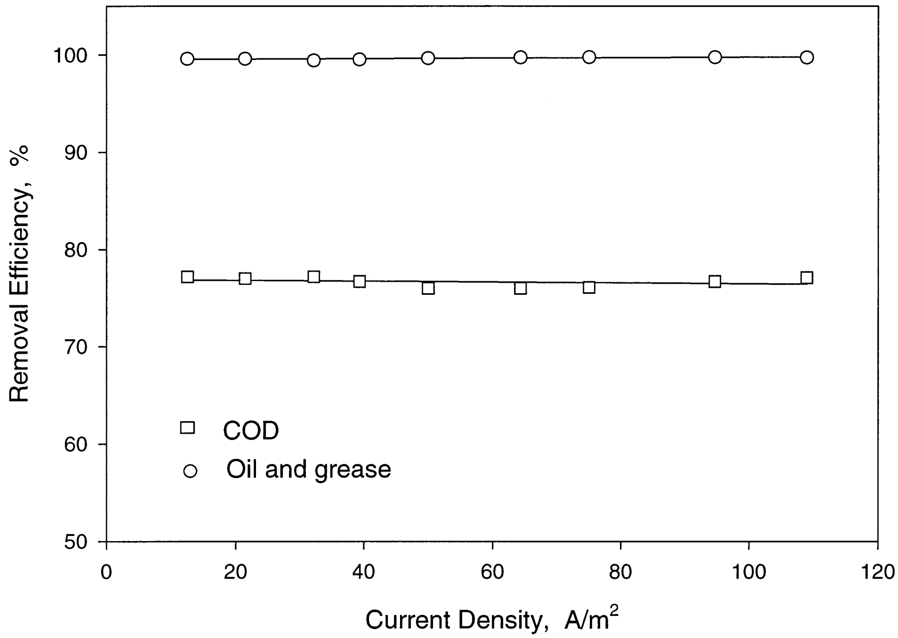

Fig. 5. Effect of current density on COD, oil and grease removal. Charge loading 6.63 F/m^3, original pH 6.95, COD 1910 mg/l, oil and grease 1200 mg/l, conductivity 769 μS/cm.

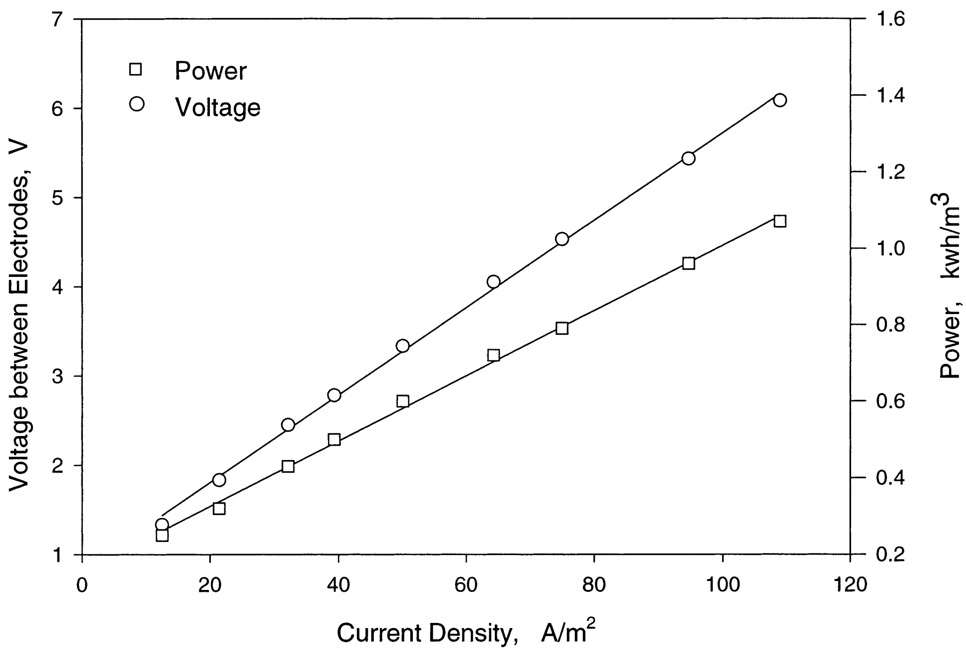

Fig. 6. Effect of current density on electrolysis voltage and power requirement. Charge loading 6.63 F/m^3, original pH 6.95, COD 1910 mg/l, oil and grease 1200 mg/l, conductivity 769 μS/cm.

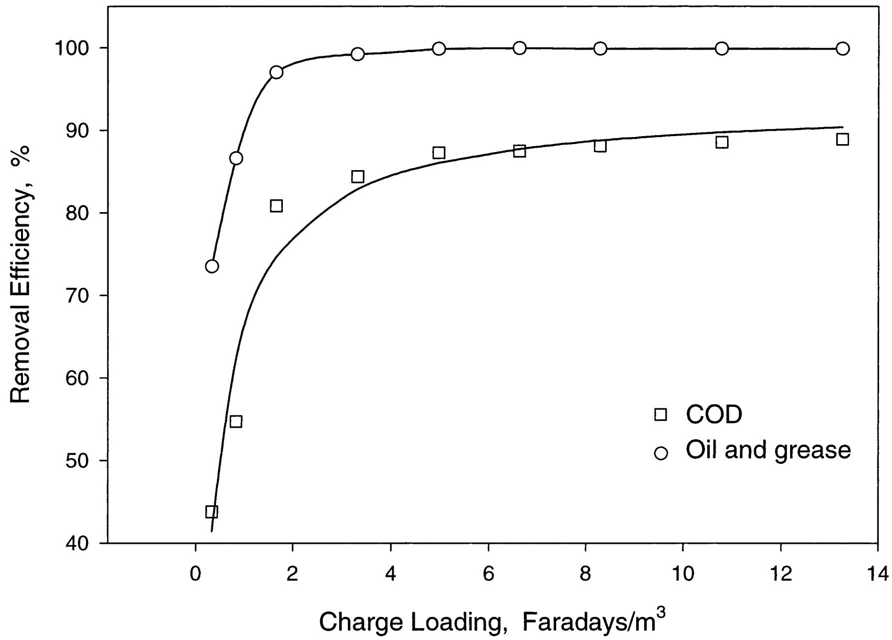

Fig. 7. Effect of charge loading on COD, oil and grease removal. Feed flow rate 9.0 l/h, original pH 6.82, COD 2380 mg/l, oil and grease 946 mg/l, conductivity 295 μS/cm.

density is 30–80 A/m^2 for Hong Kong, under which conditions the power requirement is usually < 1.5 kW h/m^3 wastewater.

3.5. *Effect of charge loading*

The mechanisms of electrocoagulation for wastewater treatment are very complex. It is generally believed that there are three other possible mechanisms involved besides electrocoagulation, i.e. electroflotation, electrochemical oxidation and adsorption [3,14]. Nevertheless, all the mechanisms highly depend on charge loading. Fig. 7 illustrates the effect of the charge loading. Sharp increases of removal efficiencies are clearly shown initially. After charge loading increased beyond 4 F/m^3, the removal efficiencies approached plateaus at 88.9% for COD and 99.9% for oil and grease. The optimum charge loading should be at the end of the sharp increase stage. In this case, it is 1.67 F/m^3. It was also observed that the effluent gradually turned visually clear at 1.67 F/m^3, and became very clear beyond 4 F/m^3. This not only implies that the optimum charge loading can be determined on the basis of visual clearness without doing COD, oil and grease measurements, but also reveals that electrocoagulation is the main mechanism for COD, oil and grease removal before the optimum charge loading achieved. The slight improvement for COD removal following a great increase in the charge loading possibly results from the adsorption and electrochemical oxidation, and is not worth the energy consumed because of the rapid increases in electrolysis voltage as shown in Fig. 8. It should be noted that the optimal charge loading might be different for different restaurant wastewater, as will be seen subsequently.

3.6. *Effect of wastewater conductivity*

In order to examine the effect of conductivity on COD, oil and grease removals, NaCl was added to wastewater to vary its conductivity. Fig. 9 shows the experimental results. It appears that conductivity had little effect on treatment efficiencies in the investigated range from 443 to 2850 μS/cm. This finding is in contrast to that reported

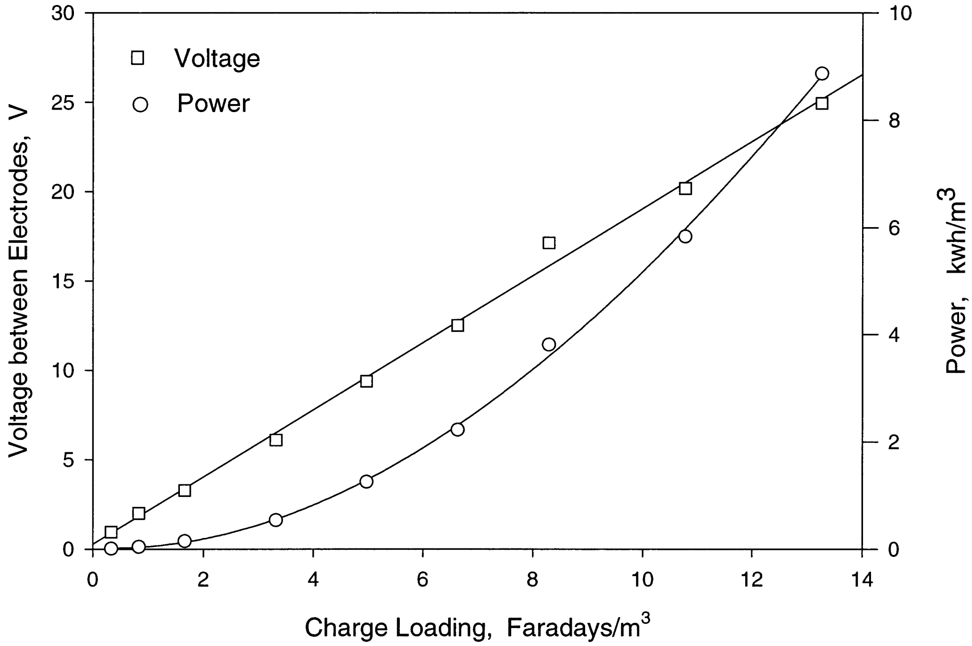

Fig. 8. Effect of charge loading on electrolysis voltage and power requirement. Feed flow rate 9.0 l/h, original pH 6.82, COD 2380 mg/l, oil and grease 946 mg/l, conductivity 295 μS/cm.

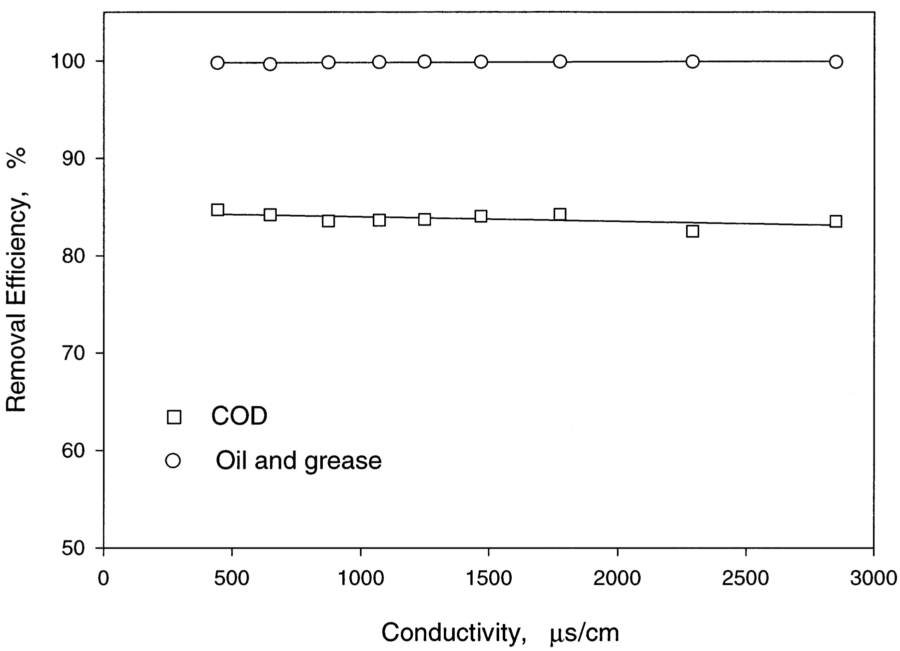

Fig. 9. Effect of conductivity on COD, oil and grease removal. Charge loading 6.63 F/m^3, feed flow rate 9.0 l/h, original pH 7.08, COD 1700 mg/l, oil and grease 1140 mg/l.

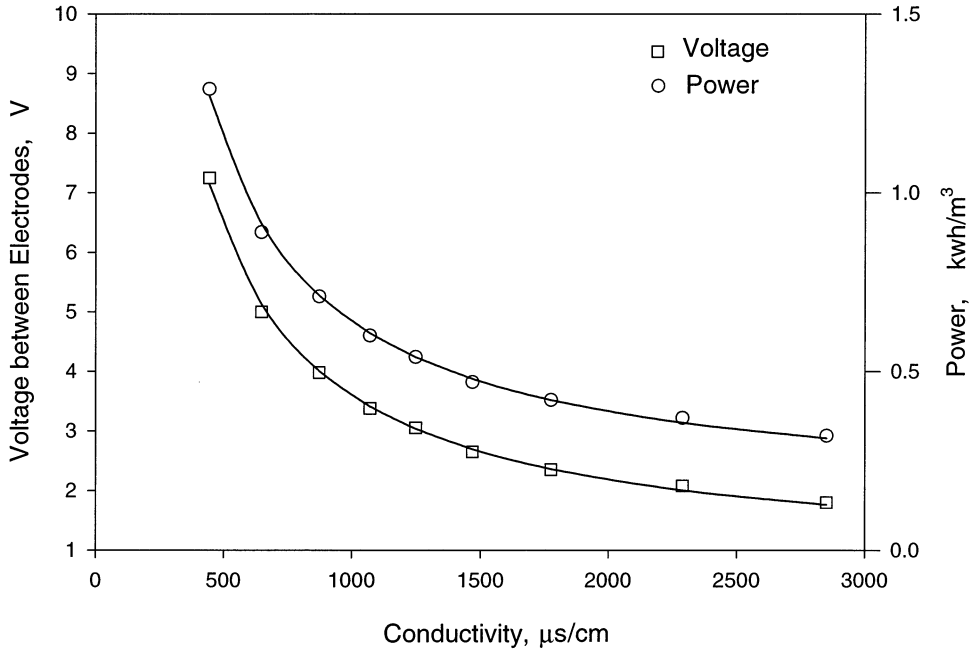

Fig. 10. Effect of conductivity on electrolysis and power requirement. Charge loading 6.63 F/m^3, feed flow rate 9.0 l/h, original pH 7.08, COD 1700 mg/l, oil and grease 1140 mg/l.

by Lin and Peng [4] for electrocoagulation of textile wastewater using iron electrodes. Such an inconsistency probably resulted from the differences in the mechanisms of pollutant removal for the two studies. As mentioned above, the pollutants are mainly removed by electrocoagulation for restaurant wastewaters, while electrochemical oxidation plays an important role in removing dyes and other organic compounds from textile wastewater.

The variation of wastewater conductivity did affect the power consumption. Fig. 10 describes the electrolysis voltage and power requirement versus the conductivity. As conductivity increased from 443 to 2850 µS/cm, the voltage between electrodes decreased rapidly from 7.25 to 1.80 V at the same charge loading; and as a result, the power requirement decreased from 1.29 to 0.32 kW h/m^3. Thus, although adding salt to the wastewater does not help increase the pollutant removal efficiency, it can save power consumption significantly.

3.7. Current efficiency

The current efficiency is defined as the ratio of the actual electrode consumption to the theoretical value. It is also an important parameter for the electrocoagulation process because it affects the lifetime of the electrodes. Theoretically, according to Faraday's law, whenever one Faraday of charge passes through the circuit, 9.0 g of aluminum is dissolved at each anode for a bipolar electrocoagulation unit. However, because of the electrochemical side-reactions, the actual electrode consumption may be reduced or increased from this theoretical value depending upon the wastewater characteristics and operational condition. For the present study, Reactions (3) and (4) tend to reduce the aluminum consumption. On the other hand, Reactions (2), (3) and (6) near the anodes and the hydrogen evolution at the cathodes, in most cases, make the wastewater acidic at anode surfaces and alkali at cathode surfaces, and thus can enhance the dissolution of aluminum through the following chemical reactions.

$$2Al + 6H^+ = 2Al^{3+} + 3H_2 \quad \text{(at acidic environment)} \qquad (8)$$

$$2Al + 6H_2O + 2OH^- = 2Al(OH)_4^- + 3H_2 \quad \text{(at alkali environment)} \qquad (9)$$

As a result, the actual electrode consumption can be greater than the theoretical value. It was measured that the actual consumption of the four aluminum electrodes was 16.52 g after 33.2 h of electrocoagulation at an average current of 0.312 A. Meanwhile, a total of 0.3864 F of charges passed through the circuit, with a theoretical consumption of 13.91 g of aluminum. Hence, the current efficiency is 118.8%. Obviously, besides electrochemical Reaction (1), chemical Reactions (8) and (9) also contribute significantly to the dissolution of aluminum electrodes to generate coagulant Al^{3+} in the electrocoagulation of the restaurant wastewater.

3.8. Amount of sludge produced in the electrocoagulation process

Similar to the chemical coagulation, most pollutants in the original wastewater did not disappear during the electrocoagulation. Accompanying the purification of the wastewater was the generation of sludge. About two thirds of the sludge floated on the top of the electrocoagulation apparatus and came out from a sludge outlet, while the other third was generated after sedimentation. The components of the sludge include suspended solids as well as oil and grease and aluminum hydroxide. After the wastewater containing COD (2764 mg/l), BOD (825 mg/l), oil and grease (1500 mg/l) and SS (574 mg/l) was treated at a charge loading of 4.97 F/m^3, the amount of the wet sludge produced was 1.93% of the treated wastewater in volume. After being dried at 105°C for 10 h and ignited at 550°C for 1 h, the residual amount of the sludge was only 0.108 kg/m^3 wastewater.

3.9. Treatment of various restaurant wastewaters

In order to get more general information re-

Table 2
Results of treatment of various restaurant wastewater

Restaurant	Chinese restaurant	Western restaurant	American fast-food	Student canteen	UC bistro
Operational parameters					
Wastewater flow (l/h)	9.0	9.0	9.0	9.0	9.0
Current (A)	0.25–0.3	0.3	0.3–0.6	0.1–0.3	0.4–0.45
Charge loading (F/m^3)	4.00–4.97	4.97	4.97–9.95	1.67–4.97	6.63–7.46
Voltage between electrodes (V)	7.05–8.63	6.58–11.5	4.33–11.6	3.95–6.25	10.4–15.5
Power requirement (kW h/m^3)	0.94–0.96	0.88–1.54	0.58–3.08	0.53–0.83	2.09–2.76
Electrode consumption (g/m^3)	42.8–53.1	53.1	53.1–106.4	17.7–53.1	70.9–79.8
Original wastewater					
pH	6.40–6.67	6.94–7.35	6.28–7.06	6.80–7.07	7.63–8.22
COD (mg/l)	606–2400	1940–2190	1150–4240	2450–2760	1500–1740
BOD$_5$ (mg/l)	167–1380	729–1160	668–2240	825–1250	451–704
Oil and grease (mg/l)	120–712	309–332	355–402	1090–1500	140–410
SS (mg/l)	35.2–193	152–339	130–218	574–578	359–388
Conductivity (μS/cm)	293–422	309–441	576–706	476–701	341–514
Effluent					
pH	7.89–8.43	8.31	7.76–8.26	8.01–8.56	8.60–8.66
COD (mg/l)	139–525	320–685	367–2420	153–453	357–443
BOD$_5$ (mg/l)	57.3–301	117–470	224–1520	54.2–304	173–209
Oil and grease (mg/l)	0.28–3.8	1.17–6.6	1.04–5.7	0.8–8.4	7.5–7.9
SS (mg/l)	5.6–6.0	5.0–13.2	4.2–9.7	5.9–9.0	10.0–10.4
Conductivity (μS/cm)	242–407	223–452	596–712	470–709	339–476

garding the performance of electrocoagulation of restaurant wastewater, various wastewaters from different restaurants were tested. For each experiment, charge loading was adjusted to the optimum value at which the effluent just turned clear. The results are presented in Table 2. It is shown that different restaurant wastewater have different values of optimum charge loading, ranging from 1.67 to 9.95 F/m^3. Except the wastewater from the American fast-food restaurant, the overall removal efficiencies of the oil and grease, SS, COD and BOD_5 were 94.4–99.9, 84.1–99.0, 68.0–94.5 and 59.3–93.4%, respectively. Although the removal of SS, oil and grease was effective, the COD and BOD_5 removal efficiencies were much lower for the wastewater from the American fast-food restaurant than for the wastewater from the other restaurants. This difference may be due to the high sucrose and glucose contents from soft drink spillage in the wastewater of the American fast-food restaurant. The dissolved organic compounds contribute more to COD than to oil and grease. Thus, despite the 99% oil and grease removal, there is still a significant amount of dissolved organic compounds remaining in the effluent for this type of wastewater.

4. Conclusion

Electrocoagulation is a feasible process for treating the restaurant wastewater, characterized by high oil and grease content, fluctuated COD, BOD_5 and SS concentrations. Aluminum electrodes are preferred for this application. The influent pH, conductivity and electrical current density do not affect the pollutant removal efficiency significantly. Charge loading is the most important operational variable. The optimal charge loading and current density are 1.67–9.95 F/m^3 and 30–80 A/m^2, depending on wastewater characteristics. The aluminum electrode consumption ranges from 17.7 to 106.4 g/m^3, and the power requirement is usually <1.5 kW h/m^3. The removal efficiency of oil and grease is over 94% for all the wastewaters tested. The electrocoagulation can neutralize wastewater pH.

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