



Electro-scrubbing volatile organic carbons in the air stream with a gas diffusion electrode

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ABSTRACT

It is demonstrated that exposing the VOC air streams to the electro-scrubbing reactor with a gas diffusion electrode leads to an efficient removal of organics. The importance order of the influence factors on the electro-scrubbing reactor performance is: conductivity, voltage and air stream flow-rate. The effective conductivity and high voltages generally are beneficial to the removal process and the air flow-rate is not a significant factor compared with the other two, indicating that the reactor might have a consistently satisfying performance within a wide range of gas volumetric load. The mass transfer of both organics and oxygen in the reactor is estimated by mathematical model, and the calculation determines the concentration boundary conditions for the 2-ethoxyethyl acetate removal: if the 2-ethoxyethyl acetate concentration in the inflow air stream holds $C_{G,i} \leq 0.7198\%$, the removal in the electro-scrubbing reactor is electrochemical reaction controlled; if $C_{G,i} > 0.7198\%$, the controlling step will be the oxygen mass transfer from the air to the liquid in the electro-scrubbing reactor. The Apparent Current Efficiency of the electro-scrubbing reactor was also determined using COD data, which is significantly higher than some commercial metal oxide electrodes, showing that the reactor is energy efficient and has the promise for the future scale-up.

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1. Introduction

Volatile organic compounds (VOCs) are the major contaminants in the waste gas, some of which are common industrial solvents and by-products and these environmentally hazardous compounds are often carcinogens and mutagens and may deplete stratospheric ozone. USA air emissions amounted to about 0.6 Mt of pollutants in 2006 which corresponded to 33.1% of the total release of pollutants in the environment (air, land, water, and underground injection) [1,2]. Because of the public and corporate pressure, environmental legislation in all major industrialized countries is indeed posing increasingly stringent standards on VOCs emissions, the satisfaction of which requires significant improvement in the current removal technologies.

The air streams contaminated with VOCs are frequently characterized by the large volume and low, varying concentrations, which make VOC recovery not possible [3,4]. The most

pertinent strategy to treat these emissions is to destruct or transfer VOCs physico-chemically or biologically. The physical-chemical technologies including condensation, incineration, absorption/stripping, adsorption, and catalytic combustion have been extensively studied to remove VOCs from gaseous streams [5–7]. However, these technologies are either costly or they simply transfer VOCs from the gas phase to another phase. Bio-filtration systems have recently emerged as an efficient and cost-effective technology for the control of VOCs emission, which has been used in Europe for many years and is considered to be a best available control technology for treating contaminated gaseous streams, while it will not work for the poisonous VOCs and it usually requires relatively longer empty bed retention time. Furthermore, factors such as inflow fluctuation, packing materials and configurations, volumetric loading rates, nutrient feed flow rates, nutrient solution pH, and air flow patterns all may affect the final performance of bio-filtration systems and make the treatment not easy to manipulate.

Recent researches have demonstrated that electrochemical methods offer an attractive alternative to traditional routes for pollutants control [8–11], since the electrolytic process is easy to control by potential and current, and such process can operate at low temperature and pressure without adding other reagents. However, reviewing literature, it is fair to say that although elec-

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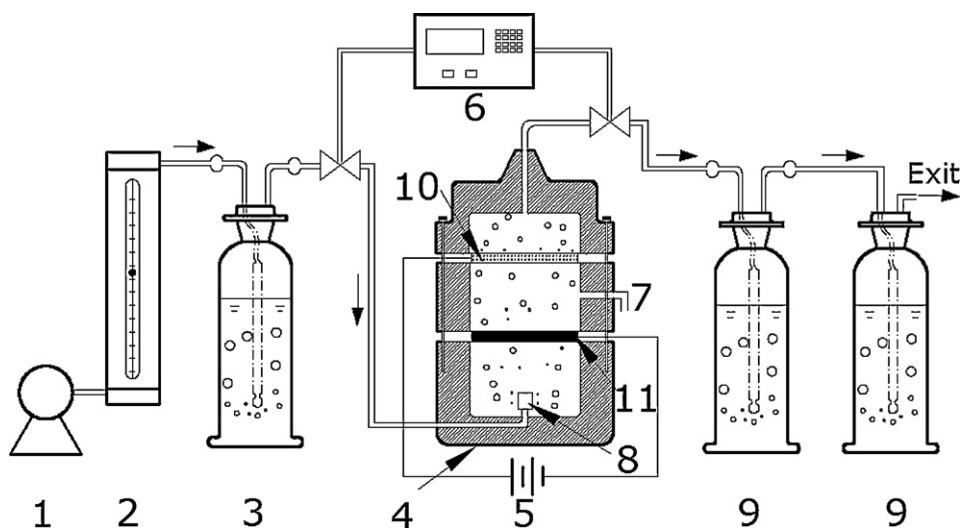


Fig. 1. The schematic diagram of the experimental setup (1) Pump; (2) Flow meter; (3) Stock solution bottle; (4) Electro-filter reactor; (5) Electricity supply; (6) Total Hydro-carbon Analyzer; (7) Sampling valve; (8) Air diffuser; (9) Washing bottle; (10) Stainless steel anode; (11) ACF cathode.

trochemical methods have been successfully commercialized, so far almost all of the efforts carried out on the electrochemical treatment pertain to the wastewaters, with primary objective of these studies being the development of appropriate parameters for contaminant removal, such as selection of electrode materials, electrolytic voltage or electrolytes [8–14]. There is a deficiency in research on the treatment of air streams containing VOCs based on electrochemical methods. It is in this context that the present study was undertaken with a primary view to propose the suitability of electrochemical methods in VOCs waste gas treatment under various conditions and explore the mechanism behind the process.

Consequently, an electro-scrubbing reactor was designed, and instead of using traditional electrodes made of metal oxide or graphite, activated carbon fiber (ACF) was employed as the cathode since it could behave as the gas diffusion electrode (GDE), which can accelerate oxygen reduction and thus have been introduced into gas consuming reactions to provide a larger reaction area and favorable conditions for gas diffusion processes [15–17]. GDEs have been widely studied in the design and manufacturing of fuel cells, especially of proton exchange membrane fuel cells and alkaline fuel cells [18–20]. The ACF GDE can greatly reduce fed oxygen in the air stream to produce hydrogen peroxide by two-electron reduction process, therefore was employed as the cathode in the electro-scrubbing reactor. The anode was stainless steel since it could leach Fe^{2+} into the reactor and form electro-Fenton pair with H_2O_2 produced at the cathode to destroy organics flowing into the reactor.

The significance of this research is trying to broaden the application of electrochemical method and explore possible industrial scale-up. The most relevant application of this strategy refers to treatment of off-gases from chemical plants, groundwater decontamination by air stripping followed by oxidation, odor emission control, and treatment of contaminated air in solvent evaporation processes. The major objectives of this study were as follows: (1) proposing an electrochemical process to remove VOCs in air streams; (2) exploring the mechanism behind the process; (3) obtaining reactor performance data under varying operating conditions such as electrolytic voltage, air flow-rate etc. and (4) calculating the current efficiency of the system. 2-Ethoxyethyl acetate (EEAc) was selected as the typical target VOCs for this study, since it is broadly used as a diluent and a cleaner in many industries because of its considerable hydrophilic and lipophilic properties, and it

is known to produce spermotoxic, fetotoxic, teratogenic, hematological and immunological effects in rats and are suspected of producing hematological effects in humans. The National Institute for Occupational Safety and Health (NIOSH) suggest that exposures to glycol ethers should be reduced to the lowest extent feasible in order to protect workers from suspected teratogenic or reproductive effects.

2. Experimental

2.1. Electro-scrubbing reactor

The experimental setup employed is shown in Fig. 1. One piece of a round ACF felt with diameter of 86 mm was employed as cathode and a porous stainless steel (standard 304 steel according to ASTM A193) sheet of same size as anode with 0.1 mm thickness. The electrodes were situated 20 mm apart from each other and the height of the reactor was 130 mm.

The air was pumped into the stock solution bottle containing 200 ml EEA solution with varying concentrations by a peristaltic pump (Model ACO-5503, Guangdong Haili Pump Company of China) to produce air streams containing EEA for electro-scrubbing reactor treatment. The flow-rate was controlled by a flow-meter (Model LZB-4, Zhejiang Zhenxing Flow-Meter Company of China). The air stream containing EEA was then introduced into the electro-scrubbing reactor through a porous aerator at the center of the reactor bottom. The reactor was filled with 500 ml Na_2SO_4 solution with a concentration of 1 g L^{-1} . The exiting gas of the reactor was absorbed by a series of two washing bottles containing 250 ml Na_2SO_4 solution each to collect the escaping EEA. At appropriate time intervals, samples of 10 ml were withdrawn from the reactor and analyzed to determine the intermediate properties of the reaction medium during the electrochemical conversion. A direct current voltage stabilized power supply (WYJ, Shanghai Songte Electrification Company of China) was connected to both the anode and cathode to control the potential.

2.2. Materials and analysis

EEAc ($\text{CH}_3\text{COOCH}_2\text{CH}_2\text{OC}_2\text{H}_5$, 98.5%) was obtained from Sino-reagent, and all the other reagents used were of analytical grade. Commercial ACF in cloth form was obtained from Nantong Sanyou

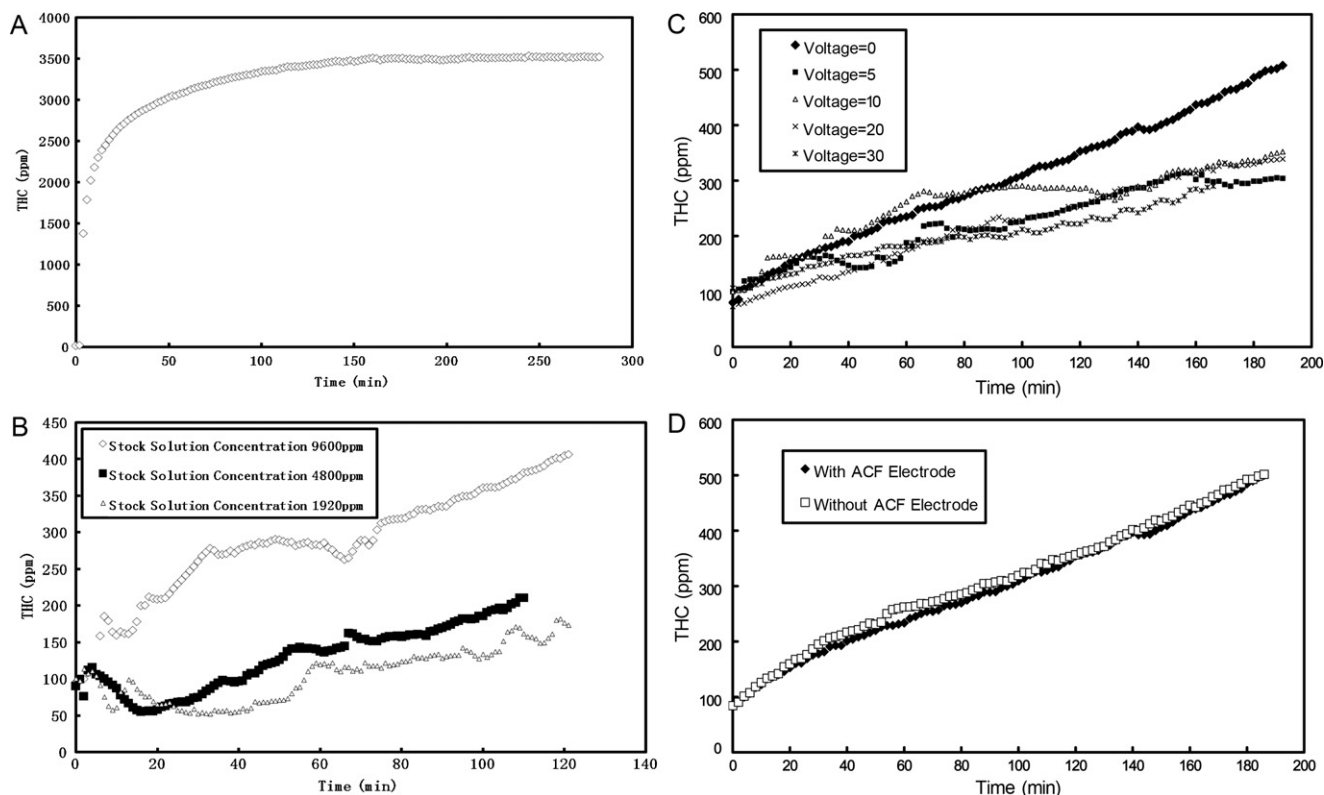


Fig. 2. (A) One typical example of the EEC concentrations in the air stream exiting the stock solution bottle (flow-rate 20 L h^{-1}); (B) the EEC concentrations in the air stream exiting the electro-filter reactor (flow-rate 20 L h^{-1} . Effect of inflow concentration (voltage = 10 V)); (C) the EEC concentrations in the air stream exiting the electro-filter reactor (flow-rate 20 L h^{-1} . Effect of voltages (the initial EEC concentration in the stock solution bottle was 9600 ppm)) and (D) the EEC concentrations in the effluent air stream from the electro-filter reactor (flow-rate 20 L h^{-1} , voltage = 0).

Environmental Technology Company of China. The average fiber diameter was around $10\text{--}20 \mu\text{m}$ and the specific area between $1000\text{--}1200 \text{ m}^2 \text{ g}^{-1}$. The ACF electrode was soaked and rinsed in de-ionized water three times, and dried in oven at 100°C before each experimental run.

The pH and dissolved oxygen (DO) in the solution was determined using pHS-3C pH meter (Shanghai Zhiguang Instrument Company of China) and Model 830A DO meter of Thermo Orion (USA). The ultraviolet (UV) was evaluated by the absorbencies of the solutions in the reactor using a UV/vis spectrophotometer (UNICO Instruments Company of China). Also chemical oxygen demand (COD) of solution samples in the electro-scrubbing reactor was obtained using potassium dichromate, $\text{K}_2\text{Cr}_2\text{O}_7$, as an oxidizing agent via Unico CT-50 COD Reactor (USA).

Gas chromatography–mass spectrometry (GC–MS) analysis process is as follows: the solution samples at different time interval were extracted using SPME [21] for GC–MS analysis. GC–MS analyses were performed using a GC MSQP 2010 apparatus (SHIMADZU Company of Japan), equipped with DB-5 MS column ($30 \text{ m} \times 0.32 \text{ mm} \times 0.25 \mu\text{m}$). The chromatographic conditions were as follows: 50 cm s^{-1} as the carrier gas (He) flow rate; 40°C as initial temperature for 5 min; 5°C min^{-1} as temperature to 280°C and keep the temperature for 6 min; 280°C as injector and transfer-line temperature. The split ratio is 1:10. MS detects at voltage 1.01 kV , EI 70 eV , scan field $33\text{--}200 \text{ m z}^{-1}$, and ion source temperature 200°C .

The organic concentration in the air steams was determined online by a hydrocarbon analyzer (51C-HT, Thermo, USA) every 2 min. The detector temperature was 200°C , sampling pump pressure at 6.50 psi , air pressure at 15 psi , and hydrogen pressure at 9.5 psi_0

3. Results and discussion

3.1. Degradation of EEC in the air streams

Fig. 2A shows one typical example of the total hydrocarbon concentrations (THC) in the air stream exiting the EEC bottle, which was filled with 9600 ppm EEC solution. The data proves that passing through the stock solution bottle could introduce a relatively stable concentration of EEC into the air for following electrochemical treatment. It could be seen that the concentration went up from almost zero to thousands quickly, indicating that the effluent from the EEC stock solution bottle was diluted by the stagnant air in the tubing and instrument initially, but became stable around 3500 ppm after about 2 h. By integrating the THC within certain time interval, the total EEC load in the air streams could be obtained. For all the following experiments, the total EEC flowing into the electro-scrubbing reactor was obtained using this method.

To further verify the effect of electro-scrubbing reactor on the EEC removal, experiments were performed with different voltages and different initial EEC concentrations in the stock solution bottle, and the results were shown in Fig. 2.

It could be seen from Fig. 2B that as the initial concentration in the stock solution bottle goes up; the effluent concentration from the electro-scrubbing reactor also increases accordingly. This is reasonable since as the stock solution concentration goes up, more EEC could be transferred into the reactor, while a linear relationship between the initial stock solution concentration and the effluent concentration could not be obtained, indicating that the electrochemical factor might make the difference. Fig. 2C shows the variation of the EEC concentrations at the electro-scrubbing reactor outlet with time at different treating voltages. It is evident that

Table 1
Orthogonal tests for EEAC removal in the electro-filter reactor.

Factors selected and the corresponding levels		1	2	3	
A	Air flow-rate (L h ⁻¹)	20	24	16	
B	Voltage (V)	20	25	30	
C	Na ₂ SO ₄ (g L ⁻¹)	0.5	1	1.5	
Results		A	B	C	COD removal (%)
1		1	1	1	56
2		1	2	2	66
3		1	3	3	56
4		2	1	2	66
5		2	2	3	63
6		2	3	1	76
7		3	1	3	45
8		3	2	1	52
9		3	3	2	47
K _{1j}		1.79	1.68	1.85	
K _{2j}		2.05	1.82	1.80	
K _{3j}		1.45	1.79	1.64	

as the voltage increases the effluent concentration from the reactor decreases, proving indirectly that electrochemical process plays an important role at decreasing the EEAC concentration. Although the figure exhibits that the EEAC decrease is more readily under higher voltages, the data alone could not demonstrate whether the EEAC is removed or not since the chemical could be absorbed by the solution in the electro-scrubbing reactor or adsorbed by the ACF electrodes. Therefore, direct evidence is needed before any further conclusion could be drawn.

Firstly, the effect of ACF adsorption was studied and the data was shown in Fig. 2D. It is evident in Fig. 2D that the adsorption by ACF electrode is trivial and negligible if the voltage is 0. Furthermore, another index was employed to study the removal of EEAC in the electro-scrubbing reactor. The COD of the solution in the reactor was examined and the total COD removal was calculated using following expression:

$$R_{\text{COD}}\% = \frac{(\text{COD}_0 - \text{COD}_S - \text{COD}_L)}{\text{COD}_0} \times 100 \quad (1)$$

COD₀: total COD entering the reactor

COD_S: COD of the solution in the reactor

COD_L: COD exiting the reactor

Orthogonal tests were performed to study the effect of some parameters on the EEAC removal in the electro-scrubbing reactor. Table 1 shows the factors selected and their corresponding levels. In orthogonal test, air flow-rate, voltage and electrolyte concentration are considered as the main factors in electro-scrubbing reactor performance.

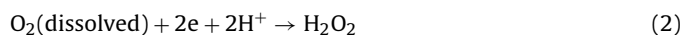
Table 1 shows the results of orthogonal test. It is evident in Table 1 that the electro-scrubbing reactor could remove a considerable amount of EEAC by mineralizing it. Since some of the organics were destructed while not totally mineralized, the apparent removal could be higher than COD removal. It was also found that in orthogonal test, the importance order of the influence factors on electro-scrubbing reactor performance was: C > B > A. The data manifests that effective conductivity in the solution is the most important factor to consider when it comes to the design of an electro-scrubbing reactor. Also, high voltages generally are beneficial to the removal process and the air flow-rate is not a significant factor compared with the other two, indicating that the reactor might have a consistent satisfying performance within a wide range of waste gas volumetric load, which is one important characteristic of the industrial VOC air streams.

3.2. Mechanism of removal

To further elucidate the possible EEAC removal path in the electro-scrubbing reactor, UV and GC-MS were employed to analyze the samples. Fig. 3 shows the typical GC-MS and UV spectrum of the samples taken at 180mins from the electro-scrubbing reactor with 20 V. The control samples were taken with all the parameters kept the same except the voltage was 0. It can be learned from Fig. 3A that the adsorption around 230 nm in the UV spectrum of the control sample is from EEAC, and after 180 min electrolysis, the adsorption weakened significantly, indicating that most of it has been removed as a chemical entity. GC-MS results in Fig. 3B prove that the composition of the non-treated solution in the reactor is complex. After 180 min electrochemical treatment, the number of components decreased significantly, which together with COD data shown in Table 1 validates that mineralization and not other process dominates the EEAC removal process.

The mechanism of electrochemical treatment process is very complicated and not yet fully understood [22]. Usually, these mechanisms involved in treatment of organics are electro-floation, electrocoagulation and electro-oxidation at the anode.

Previous work has proven that when air diffuses through active layer on the ACF as a cathode, oxygen is reduced to hydrogen peroxide [23–25]. The reduction of oxygen to form hydrogen peroxide happens with a high yield only on cathodic materials, including carbon, gold and mercury.

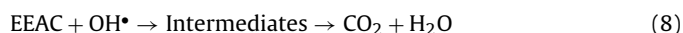


The Fe²⁺ dissolves from anode could react with H₂O₂ to form free radical for the oxidation of organics [26],



It is a chain reaction, step (3) serving as chain initiation, steps (6) and (7) as termination. The cycle (3)–(4)–(5) forms the chain, which is the site of O₂ evolution.

Based on the above THC, COD, UV and GC-MS results, it is reasonable to presume that electro-Fenton is the major pathway for EEAC removal as follows:



And the overall process of EEAC removal from air streams in electro-scrubbing reactor could be proposed as follows: absorption of EEAC by the solution in the reactor → production of H₂O₂ through the GDE → dissolution of Fe²⁺ from the anode → formation of electro-Fenton pairs to produce OH• → EEAC oxidized by OH• generated in the reactor as shown in Fig. 4. Therefore, the above-mentioned electrochemical control is indirect: it arises from the reaction of species produced at the anode (Fe²⁺) and cathode (H₂O₂) to produce OH• which then oxidizes the VOC.

3.3. Mass transfer boundary conditions

In commonly encountered situations, in which the desired final organic levels are low, and under the most frequently applied Galvan static operation conditions, the oxidation of the target organic compound may become mass transfer controlled either from the very beginning or soon after the start-up of the process. And this might reduce the current efficiency of the electrochemical reactor and waste the energy on water electrolysis. Therefore, the boundary conditions for the mass transfer should be explored for the reactor

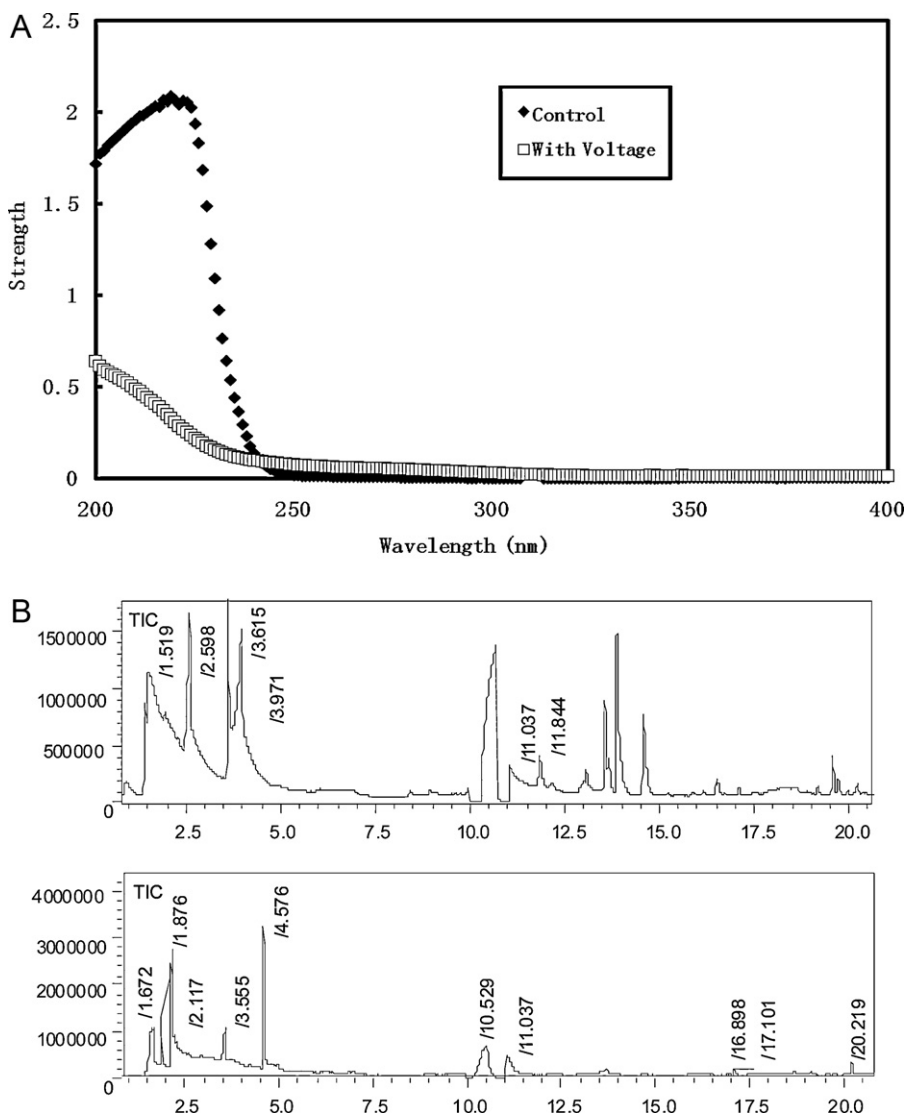


Fig. 3. (A) The UV results of solutions in the electro-filter reactor (the initial EEC concentration in the stock solution bottle was 9600 ppm, flow-rate 20 L h⁻¹, voltage = 0, 20) and (B) the GC-MS results of solutions in the electro-filter reactor (the initial EEC concentration in the stock solution bottle was 9600 ppm, flow-rate 20 L h⁻¹, voltage = 0, 20).

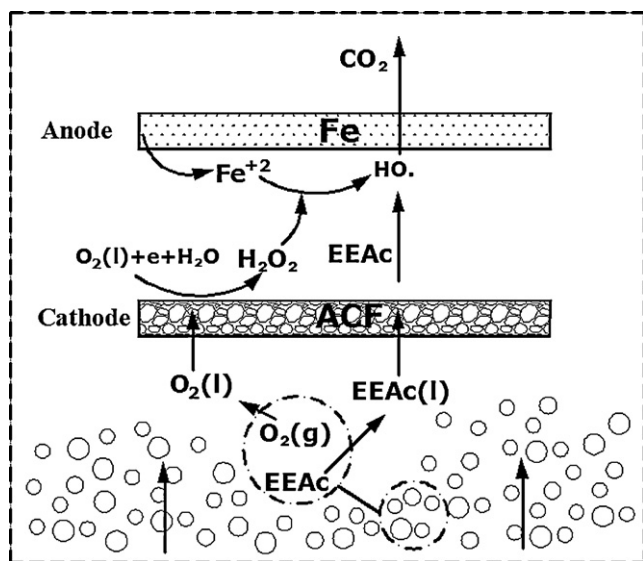


Fig. 4. Degradation pathway of 2,4-DCP.

design. As shown in Eq. (4), the conversion of EEC in the electro-scrubbing reactor allows to regenerate continuously the scrubbing liquid and to maintain a driving force to improve mass transfer, while the consumption of DO could limit further mineralization. Therefore, the DO is critical for the efficient EEC oxidation. Since the saturation level of DO is in the order of ppm, the transfer from the air stream is the dominant source for O₂ supply. When the VOC concentration is low in the air stream, the electro-scrubbing reactor could efficiently mineralize the organics as shown in above figure and table. However, if the organic concentration is high, the mass transfer of O₂ could be the limiting factor. As to how high the EEC concentration could be for satisfying removal, the mass transfer for both EEC and O₂ from gas phase to liquid phase should be calculated to estimate the boundary conditions.

Generally, the total mass transfer rate of O₂ from air to liquid in the electro-scrubbing reactor could be described as:

$$\frac{dC_{O_2}}{dt} = K_L a_{O_2} \times (C_{G,O_2} - C_{L,O_2}) \quad (9)$$

in which $K_L a_{O_2}$ is the overall mass transfer coefficient between gas and liquid phase (S^{-1}) for O₂, C_{G,O_2} is the gas phase concentration and C_{L,O_2} is the liquid phase concentration.

Eq. (5) could be simplified to following equation since C_{G,O_2} is around 21% for the air and C_{L,O_2} is about 8 ppm for water under room temperature.

$$\frac{dC_{O_2}}{dt} = 0.21 \times K_L a_{O_2} \quad (10)$$

The correlation proposed by Alexander and Shah [27] could be used to calculate the overall mass transfer coefficient of oxygen, $K_L a_{O_2}$ from the gas phase to the liquid phase:

$$K_L a_{O_2} = 0.06371 \times (V'_L)^{0.3014} \times (V'_G)^{0.4484} \quad (11)$$

in which V'_L equals liquid-phase superficial mass velocity ($\text{kg m}^{-2} \text{s}^{-1}$) and V'_G is equal to gas-phase superficial mass velocity ($\text{kg m}^{-2} \text{s}^{-1}$).

The mass transfer rate of EEAc from gas phase to liquid phase in the electro-scrubbing reactor is expressed as follows:

$$\frac{dC_i}{dt} = K_L a_i \times (C_{G,i} - C_{L,i}) \quad (12)$$

in which $K_L a_i$ is the overall mass transfer coefficient between gas and liquid phase (S^{-1}) for EEAc, $C_{G,i}$ is the gas phase concentration and $C_{L,i}$ is the liquid phase concentration.

And the following equation can be derived from the two film theory and was used to calculate the overall mass transfer coefficient, $K_L a_i$ for EEAc (S^{-1}):

$$K_L a_i = K_L a_{O_2} \times \left(\frac{D_{L,i}}{D_{L,O_2}} \right)^{0.5} \times \left[1 + \frac{1}{H_i (k_{g,i}/k_{l,i})} \right]^{-1} \quad (13)$$

in which $K_L a_{O_2}$ is determined as shown above, $D_{L,i}$ equals the liquid diffusivity of compound i ($\text{cm}^2 \text{s}$), D_{L,O_2} is equal to the liquid phase diffusion coefficient of oxygen ($\text{cm}^2 \text{s}$), H_i equals the Henry's law constant of EEAc (dimensionless), and $k_{g,i}/k_{l,i}$ equals the ratio

$$\frac{dC_{O_2}}{dt} / \frac{dC_i}{dt} = \frac{0.21 \times [1 + (1/3H_i)]}{((13.26 \times 10^{-5} / \mu^{1.14} \times V_b^{0.589}) / ((3.25 \times 10^{-5} \times 0.0089 \times \text{Temperature}) / 298.15 \times \mu))^{0.5} \times (C_{G,i} - C_{L,i})} \geq 4.5 \quad (18)$$

of gas phase mass transfer coefficient to liquid phase mass transfer coefficient for EEAc (dimensionless). Methods for determining values for $D_{L,i}$, D_{L,O_2} , H_i and $k_{g,i}/k_{l,i}$ are discussed below.

Hsieh et al. [28] reported that the ratio of $k_{g,i}/k_{l,i}$ was relatively constant for bubble aeration and was observed to be between 2.2 and 3.6. Consequently, a conservative value of 3.0 was assumed for $k_{g,i}/k_{l,i}$ because mass transfer was very fast.

$D_{L,i}$ was determined from the correlation presented by Hayduk and Laudie [29]:

$$D_{L,i} = \frac{13.26 \times 10^{-5}}{\mu^{1.14} \times V_b^{0.589}} \quad (14)$$

in which μ equals viscosity of liquid water (centipoise) and V_b is equal to molar volume at the normal boiling point ($\text{cm}^3 \text{g mol}^{-1}$). D_{L,O_2} was adjusted with temperature and water viscosity (D_{L,O_2} at 25°C (298.15 K) is $3.25 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, and the viscosity of water at 25°C (298.15 K) is $0.0089 \text{ g cm}^{-1} \text{ s}^{-1}$):

$$D_{L,O_2} = \frac{3.25 \times 10^{-5} \times 0.0089 \times \text{Temperature}}{298.15 \times \mu} \quad (15)$$

in which and temperature is in degrees Kelvin (K).

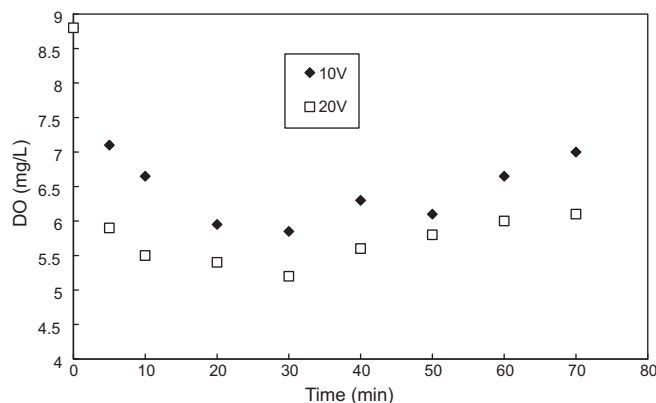


Fig. 5. The DO in the electro-filter reactor (the initial EEAc concentration in the stock solution bottle was 9600 ppm, flow-rate 20 L h^{-1}).

For the total mineralization of 1 mol EEAC, stoichiometrically 4.5 mol of O_2 are needed. Therefore, to guarantee enough O_2 supply for the oxidation, following condition must be hold:

$$\frac{dC_{O_2}}{dt} / \frac{dC_i}{dt} = \frac{0.21 \times K_L a_{O_2}}{K_L a_i \times (C_{G,i} - C_{L,i})} \geq 4.5 \quad (16)$$

Eq. (16) could be changed as follows:

$$\frac{dC_{O_2}}{dt} / \frac{dC_i}{dt} = \frac{0.21 \times [1 + (1/(H_i \times (k_{g,i}/k_{l,i})))]}{(D_{L,i}/D_{L,O_2})^{0.5} \times (C_{G,i} - C_{L,i})} \geq 4.5 \quad (17)$$

Insert Eq. (14) and Eq. (15) into Eq. (17), following relationship could be obtained:

If the initial EEAc concentration in the electro-scrubbing reactor is zero, the highest air stream concentration of EEAc that the reactor could handle is:

$$C_{G,i} \leq \frac{0.21 \times [1 + (1/3H_i)]}{4.5 \times ((13.26 \times 10^{-5} / \mu^{1.14} \times V_b^{0.589}) / ((3.25 \times 10^{-5} \times 0.0089 \times \text{Temperature}) / 298.15 \times \mu))^{0.5}} \quad (19)$$

Assuming the temperature is 298.15 K, following result could be obtained:

$$C_{G,i} \leq 0.7198\% \quad (20)$$

and this is the concentration limit for controlling process: if $C_{G,i} \leq 0.7198\%$, the removal is electrochemical reaction controlled; if $C_{G,i} \geq 0.7198\%$, the controlling step will be the oxygen mass transfer from air to liquid in the electro-scrubbing reactor. The result also proves that the electro-scrubbing reactor could handle VOC air stream with fairly wide concentration range, 0–0.7198%, which is another characteristics of the industrial VOC air streams.

Fig. 5 shows the typical DO levels in the electro-scrubbing reactor during treatment of the EEAc air streams. It could be learned that although the inflow THC in the air was around 3500 ppm, DO in the electro-scrubbing reactor remained stable and adequate, indicating that the treatment was electrochemical reaction controlled. It is also evident that the DO with 20V was slightly lower than that with 10V, and that could be attributed to the higher temperature caused by electrolyzing in the reactor with 20V, which was about 10°C higher averagely.

Table 2
The ACEs of EEAc removal in the electro-filter reactor.

Voltage (V)	Flow-rate (L h ⁻¹)	Stock solution concentration (ppm)	ACE (%)
10	20	9600	73.64
15	20	9600	58.43
20	20	9600	38.23

3.4. Apparent current efficiency (ACE) of the electro-scrubbing reactor

The ACE is one major consideration when it comes to the industrialization of the electrochemical reactor design. The ACE of the electrochemical processes is defined as the current fraction used for the organic compound oxidation [30]. The current efficiency is calculated according to the COD values of the samples, and could be determined as follows [30,31]:

$$CE(\%) = F \frac{(\text{COD}_0 - \text{COD}_S - \text{COD}_L)}{8I\Delta t} \times 100 \quad (21)$$

where I is the current (A); F is the Faraday constant (96,487 C mol⁻¹); t is the treatment time (s); U is the voltage (V).

Table 2 shows the changes of current efficiency with varying voltages. It could be seen that relatively higher ACE was achieved under lower flow-rate, while all of the data shows that the reactor has significantly higher energy efficiency than the reported values (10–21%) on other systems using commercially available electrode materials such as Ti/RuO₂, Ti/IrO₂, Pt, SnO₂, PbO₂ and Si/BDD electrodes [32–34].

4. Application prospect

An electro-scrubbing reactor is designed to meet two major challenges of the industrial VOC air streams: large volume and varying concentrations. It is demonstrated that exposing VOC air streams to the electro-scrubbing reactor leads to efficient removal of organics in the inflow. The ACE of the electro-scrubbing reactor was also determined using the COD data, showing that the reactor is energy efficient and has the promise for future scale up. In our future work, we will explore the possibility of applying this technique to treat various air streams containing environmentally important organic pollutants. Although the current research is still at lab scale stage, it has promise for application considering its energy efficiency, and the commercialization of this technique is a goal worth pursuing.

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