Journal of Hazardous Materials 167 (2009) 553–559

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Stripping of organic compounds from wastewater as an auxiliary fuel of regenerative thermal oxidizer

Meng-Wen Chang, Jia-Ming Chern*

Department of Chemical Engineering, Tatung University, 40 Chungshan North Road, 3rd Section, Taipei 10452, Taiwan

ARTICLE INFO

Article history:
Received 9 July 2008
Received in revised form
27 November 2008
Accepted 7 January 2009
Available online 16 January 2009

Keywords:
VOCs
Organic solvent
RTO
COD
PCB wastewater

ABSTRACT

Organic solvents with different volatilities are widely used in various processes and generate air and water pollution problems. In the cleaning processes of electronics industries, most volatile organic compounds (VOCs) are vented to air pollution control devices while most non-volatile organic solvents dissolve in the cleaning water and become the major sources of COD in wastewater. Discharging a high-COD wastewater stream to wastewater treatment facility often disturbs the treatment performance. A pretreatment of the high-COD wastewater is therefore highly desirable. This study used a packed-bed stripping tower in combination with a regenerative thermal oxidizer to remove the COD in the wastewater from a printed circuit board manufacturing process and to utilize the stripped organic compounds as the auxiliary fuel of the RTO. The experimental results showed that up to 45% of the COD could be removed and 66% of the RTO fuel could be saved by the combined treatment system.

1. Introduction

In the electronics or other traditional industries, organic solvents play important roles. They are frequently used as raw materials, diluents, or cleaning agents for the products or manufacturing equipment. Since organic solvents are widely used in various processes, they cause air and water pollution problems inevitably. For example, in the cleaning processes of electronic industries, most volatile organic compounds (VOCs) are vented to air pollution control devices while most non-volatile organic solvents can dissolve in the cleaning water and are directly discharged into wastewater collecting systems and thus become the major sources of COD in the wastewater [1]. Part of VOCs could also dissolve in the cleaning water and becomes the minor sources of COD in the wastewater.

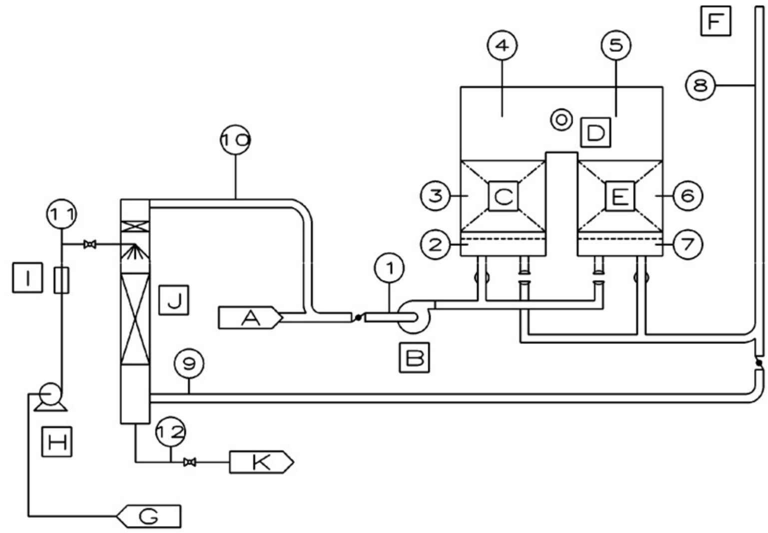
The emitted VOCs are usually treated by water scrubbing, chemical scrubbing, fixed-bed activated carbon adsorption, activated carbon fiber adsorption, condensation, thermal oxidation, or catalytic thermal oxidation [2,3]. Although activated carbon adsorption processes are quite effective for VOC abatement, spent carbon regeneration is not easy and usually causes secondary pollution problem. Due to the difficulty of regenerating spent carbon, complete combustion of VOCs into harmless CO_2 and H_2O by thermal oxidation or catalytic thermal oxidation has become an attractive choice of VOCs control. Particularly, regenerative thermal oxidizers (RTO) have been widely used for VOC control in industries with heat recovery up to 95% [4–8]. When the VOC concentration fed to RTO is above 3% of its lower explosion limit (LEL), the RTO system can maintain its normal performance and completely combust the VOCs to carbon dioxide and water without supplementary fuel. However, extra fuel is needed in RTO system to maintain at a sufficiently high temperature if the influent VOC concentration is not high enough.

In activated sludge wastewater treatment process, sufficient oxygen must be provided to maintain microbial activity by mechanical aerators or diffused aeration systems that produce vigorously turbulent gas-liquid interfaces to allow oxygen transferred from the atmospheric air to the wastewater. During aeration, oxygen is transferred into the wastewater while the pre-dissolved VOCs will emit to the atmospheric air from the wastewater simultaneously [9–12]. Aeration was viewed as a good method to remove VOC in wastewaters before, but emitted VOCs become air pollution problems of great concern now. The major source of COD resulted from the dissolved non-volatile solvents in the cleaning process wastewater cannot be removed by aeration and causes great loading to the activated sludge process. A pretreatment to remove part of the COD from process wastewater is highly desired to maintain the normal operation of the activated sludge process.

In order to solve the water and air pollution problems simultaneously in electronic or other manufacturing processes, this study aimed at stripping the dissolved volatile and non-volatile organic compounds from wastewater by the tail gas of a RTO and using the stripped organic compounds as the auxiliary fuel of the RTO.

* Corresponding author. Tel.: +886 2 2182 2928x6277; fax: +886 2 25861939.
E-mail address: jmchern@ttu.edu.tw (J.-M. Chern).

0304-3894/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2009.01.025



A	Process air	1	Thermocouple for Fan inlet
B	Process fan	2	Thermocouple for Heat exchange bed A inlet and outlet
C	Heat exchange bed A	3	Thermocouple for Heat exchange bed A
D	Burner	4	Thermocouple for Combustion chamber close to bed A
E	Heat exchange bed B	5	Thermocouple for Combustion chamber close to bed B
F	Exhaust stack	6	Thermocouple for Heat exchange bed B
G	VOC wastewater	7	Thermocouple for Heat exchange bed B inlet and outlet
H	Feed pump	8	Thermocouple for Exhaust stack
I	Flow indicator	9	Thermocouple for Stripper gas inlet
J	Stripper	10	Thermocouple for Stripper gas outlet
K	To wastewater treatment plant	11	Thermocouple for Stripper liquid inlet
		12	Thermocouple for Stripper liquid outlet

Fig. 1. Schematic diagram of the gas stripping and incineration system.

Since the solubilities of most gases in water decrease with increasing temperature, the hot tail gas from the RTO could possibly strip off the dissolved volatile and non-volatile organic compounds from wastewater. An experimental unit consisting of a gas stripping tower and a RTO was implemented in a cleaning process generating VOCs as air pollutants and wastewater with very high-COD concentration. The COD stripping efficiencies at varying feed COD concentrations, gas to liquid flow ratios, and tail gas temperatures were determined to study the feasibility of stripping the dissolved organic compounds from wastewater as the auxiliary fuel of the RTO.

2. Experimental

2.1. Apparatus

The primary purpose of this study was to test the feasibility of stripping organic compounds from high-COD wastewater to serve as the auxiliary fuel of the RTO. Because the experiments need a massive quantity of wastewater, it is impossible to be carried out in the laboratory. Therefore, a test system consisting of a gas stripping unit and a gas incineration unit was installed nearby the wastewater treatment facility of a printed circuit board (PCB) manufacturing company located in southern Taiwan. The wastewater leaving the stripping tower was directly sent to the existing wastewater treatment facility.

2.1.1. Gas stripping unit

The gas stripping unit consisted of a wastewater storage tank, a delivery pump, a padding structure load body, padding, a high-pressure spray nozzle, a demister, and associated pipeline system, as shown schematically in Fig. 1. The wastewater storage tank was used to receive wastewater from the PCB cleaning process and to provide a constant-flow wastewater stream to the high-pressure spray nozzle by the delivery pump. A valve was installed in the recycle loop to regulate the wastewater flow rate to obtain desired gas to liquid flow ratio. The demister was used to intercept the water droplets carried by the upflow gas for the purpose of not decreasing the gas combustion efficiency in the RTO. During operation, the feed wastewater was sprayed by the nozzle and flowed downward while the hot RTO tail gas flowed countercurrently from the bottom to the top of the tower. The packings in the tower provided sufficient gas-liquid contact surface area that enhanced the dissolved organic compounds stripping rate. The detailed specifications of the stripping tower used in this study are listed in Table 1.

2.1.2. Gas incineration unit

The regenerative thermal oxidizer used in this study contained two beds made of high rigid steel. The bed interiors were insulated by ceramic fiber and packed with high-efficiency and thermally stable ceramic material. A combustion chamber equipped with a burner linked the two regenerative beds. An airflow distribution chamber was used to control the gas feed to the regenerative beds.

Table 1
Characteristics of regenerative thermal oxidizer and stripper.

RTO	Main body	2000 mmL*1400 mmW*1600 mmH
	Design flow rate	20 ACMM
	Main body pressure drop	400 mm H_2O
	Main blower	Q = 20 ACMM, Sp = 450 mmAq, 7.5Hp, 220 V
	Combustion air blower	Q = 6ACMM, Sp = 625 mmAq, 3 Hp, 220 V
Stripper	Main body size	300 mmD*2265 mmH
	Wastewater process load	0–16 Liter per minute (lpm)
	Main body pressure drop	Approximately 400 mm H_2O
	Packing height	1000 mm
	Demister height	300 mm

After the stripper exhaust gas entered the distribution chamber, it was uniformly distributed and flowed into one of the two regenerative beds. The entering waste gas was heated by the hot ceramic packings in the bed to approach combustion temperature. The stripped organic compounds were then completely decomposed in the combustion chamber. After combustion, the combustion gas entered the other bed to heat the ceramic packings in order to recover the combustion heat. The stripper exhaust gas switched its inflow direction every 1–8 min depending on the desired bed temperature by a Poppet valve to one of the two regenerative beds so that the combustion temperature could maintain at stable level to decompose the inflow organic compounds. The detailed specifications of the RTO unit are also listed in Table 1. The specifications of the packing material are shown in Table 2. Using the airflow velocity suggested by the packing manufacturer at 1.32 m/s and the packing height of 2.6 m, the pressure drop over the regenerative bed was calculated to be 625 mm H_2O head.

2.2. Source of wastewater

The high-COD wastewater with major composition of 30–50% diethylene glycol monobutyl ether ($C_8H_{18}O_3$) and 10–20% glycol ($C_2H_6O_2$) came from one of the processes in the PCB manufacturing company located in southern Taiwan. Because diethylene glycol monobutyl ether and glycol contain hydroxyl groups, they are miscible with water in all proportions at the room temperature.

2.3. Experimental procedures

After completing the assembly of the experimental apparatus, the following experiments were carried out.

Table 2
Chemical composition and physical properties of the ceramic packing.

Chemical composition	SiO_2	70% by weight
	Al_2O_3	23% by weight
	Fe_2O_3	<1% by weight
	CaO	1–2% by weight
	$K_2O + Na_2O$	2–4% by weight
Physical properties	Specific gravity	2.25–2.35
	Water Absorption, % (ASTM C373)	<0.5
	Acid-resisting strength % wt. loss (ASTM C279)	<4
	Firing temperature (°C)	1250–1300
	Softening point (°C)	>1400
	Density (kg/m^3)	2300
	Specific surface area (m^2/m^3)	252
	Void fraction (%)	73
	Heat transfer coefficient (kcal/min m^3 °C)	37.5
	Maximum working temperature (°C)	1400

2.3.1. Air blower performance test

- Inspected the pipeline system of the air blower to ensure all the pipelines are adequately installed.
- Started the air blower.
- Adjusted the air blower inverter (frequency regulator) from 15 Hz to 60 Hz and record the entrance air speeds.
- Calculated the airflow rates at different air blower frequencies to establish the calibration curve of the air blower.

2.3.2. Heat recovery efficiency test

- Started up the system by a diesel-fueled burner.
- Recorded the temperatures at different locations when the system reached steady-state operation.

2.3.3. Gas stripping test

- Started up the RTO. Recorded the inlet and outlet water temperatures. Took the inlet and outlet wastewater samples for COD analysis.
- Recorded the RTO oil consumption.
- Adjusted the main blower inverter to get desired tower entrance airflow rate.
- Started up the wastewater delivery pump. Adjusted the water flow regulator to get a desired tower entrance wastewater flowrate.
- Adjusted the RTO discharge temperature to get a desired tower entrance gas temperature.
- Started to record the water outlet and gas outlet temperatures and took three wastewater samples from the top, middle, and bottom of the stripping tower, respectively for COD analysis.

3. Results and discussion

3.1. RTO performance test

In order to obtain the desired flowrate of the RTO tail gas entering the stripping tower, the frequency of the blower inverter was varied and the corresponding entrance airflow rate was recorded. A calibration curve of the blower inverter was thus developed and is shown in Fig. 2. Using the following correlation equations, the desired airflow velocity and flow rate to the stripping tower could be obtained by controlling the inverter frequency:

$$v = -1.20 + 0.338f \tag{1}$$

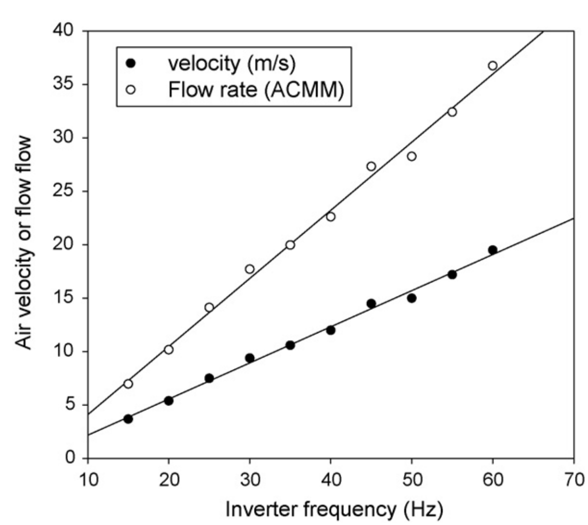


Fig. 2. The calibration curve of the blower inverter.

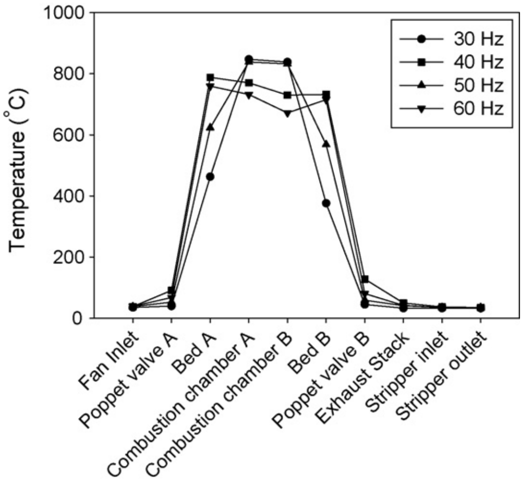


Fig. 3. Effect of the inverter frequency on the air temperatures at different RTO locations.

$$Q = -2.27 + 0.637f \quad (2)$$

After the blower inverter was calibrated, the RTO was tested for its heat recovery efficiency. In this series of tests, there was no VOC in the inlet air; diesel fuel was used in the combustion chamber with a consumption rate at 3.15 kg/h. The air temperatures at different RTO locations and inverter frequencies are shown in Fig. 3. As shown in Fig. 3, the air temperature in the fan inlet as shown by (1) in Fig. 1 equals the room air temperature. The air temperature before entering bed A as shown by (2) in Fig. 1 is slightly increased by the fan. When the air enters bed A, the temperature is sharply increased, as shown by temperature measured at point (3) in Fig. 1. For a lower air flow rate (a lower blower inverter frequency e.g. 30 Hz), the air temperature continues to be heated in the combustion chamber as shown by (4) in Fig. 1. However the air temperature decreases for a higher air flow rate because heat of fuel combustion is carried out by the large air flow rate. For all the air flow rates used, the air temperature in the combustion chamber nearby bed B as shown by (5) in Fig. 1 is lower than that nearby bed A because the burner located in the combustion chamber is closer to bed A. The air temperature in bed B shown by (6) in Fig. 1 continues to decrease due to heat transfer to the ceramic packings in bed B. The exhaust temperature leaving bed B becomes much lower as shown by the temperatures measured at point (7) and (8) in Fig. 1. In the RTO performance test, the gas stripping unit was not operated, i.e., no wastewater flowed through the stripping tower, the air temperatures at the stripper inlet and outlet remain the same as that in the exhaust stack as shown in Fig. 3. It is important to note that all the temperature profiles using the four inverter frequencies are quite similar. However, the maximum temperatures at the combustion chamber nearby the two beds as shown by (4) and (5) in Fig. 1 are higher for lower converter frequencies used.

From the data listed in Table 3, the heat recovery efficiencies under varying operating conditions can be calculated by the following equation and the results are also shown in Table 3.

$$\eta = \frac{T_C - T_{out}}{T_C - T_{in}} \quad (3)$$

where T_C is the averaged temperature in the combustion chamber, T_{in} and T_{out} are the inlet and outlet temperatures, respectively.

As is shown by the last row in Table 3, all the heat recovery efficiencies are very high. The heat recovery efficiency of this RTO unit slightly decreases with increasing inlet air flow rate, but even at a high flow rate, the heat recovery efficiency is up to 95%. This very high heat recovery performance makes us to use the RTO in combination with the stripping tower confidently.

3.2. Stripping of PCB wastewater

The wastewater containing diethylene glycol monobutyl ether and glycol was fed to the stripping tower to remove its COD. A preliminary test up to 8 h operation showed that the outlet water temperature, outlet gas temperature reached steady-state within 30 min while the COD concentration in the treated wastewater linearly decreased with operating time and became almost constant after 2 h operation. Due to the size limitation of the wastewater storage tank, the maximum operating time for other test runs was set to be 2 h to obtain enough wastewater quantity of the same wastewater quality (organic compound composition, COD, temperature etc.).

In order to quantify the stripping tower performance, the COD removal efficiency and the COD removal rate were calculated by the following equations, respectively:

$$\text{Removal efficiency} = \frac{COD_{in} - COD_{out}}{COD_{in}} \times 100\% \quad (4)$$

$$\text{Removal rate} = L(COD_{in} - COD_{out}) \quad (5)$$

where L is the wastewater feed flow rate, COD_{in} and COD_{out} are the inlet and outlet COD concentrations, respectively.

Using these definitions, the COD removal efficiencies at 30 °C inlet water temperature, 4.71 ACMM inlet gas flowrate, and other varying operating conditions are shown in Figs. 4 and 5. Fig. 4 shows that after 120 min operation, the COD removal efficiency at 30 °C inlet gas temperature is higher for a lower water flow rate; the COD removal efficiency at 200 °C inlet gas temperature is lower for a lower water flow rate. The organic stripping rate can be calculated by the following equation:

$$\text{Organic stripping rate} = K_L a(C_i - C_i^*) \quad (6)$$

Table 3
Temperature profiles under varying operating conditions.

Location	Operation				
	Burner off	30 Hz 17.7 ACMM	40 Hz 22.6 ACMM	50 Hz 28.3 ACMM	60 Hz 36.8 ACMM
Fan inlet (1)	35 °C	35 °C	38 °C	38 °C	39 °C
Poppet valve A (2)	37 °C	40 °C	91 °C	43 °C	68 °C
Bed A (3)	42 °C	463 °C	788 °C	623 °C	759 °C
Combustion chamber close to bed A (4)	45 °C	847 °C	770 °C	838 °C	732 °C
Combustion chamber close to bed B (5)	43 °C	838 °C	730 °C	832 °C	672 °C
Bed B (6)	41 °C	376 °C	732 °C	568 °C	715 °C
Poppet valve B (7)	38 °C	45 °C	128 °C	59 °C	81 °C
Exhaust stack (8)	36 °C	33 °C	50 °C	41 °C	42 °C
Stripper inlet (9)	35 °C	33 °C	37 °C	35 °C	35 °C
Stripper outlet (10)	35 °C	33 °C	35 °C	35 °C	34 °C
Heat recovery	NA	99.4%	94.4%	98.0%	97.9%

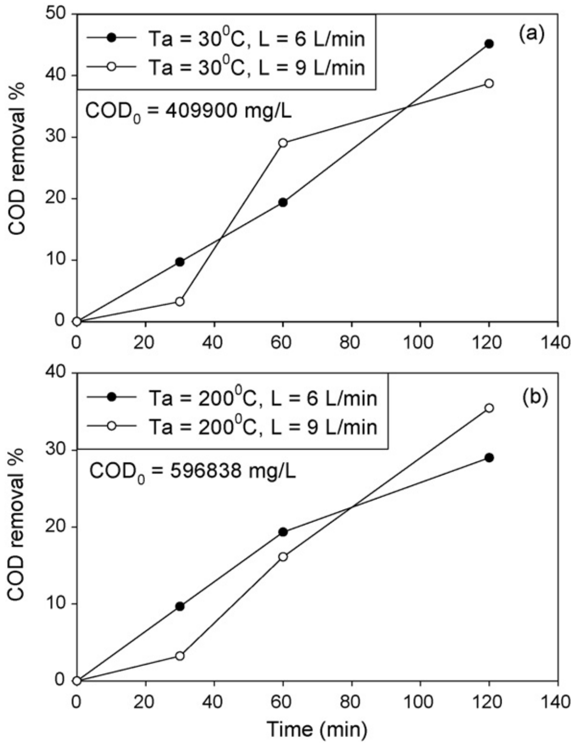


Fig. 4. The effect of water flow rate on the COD removal efficiency.

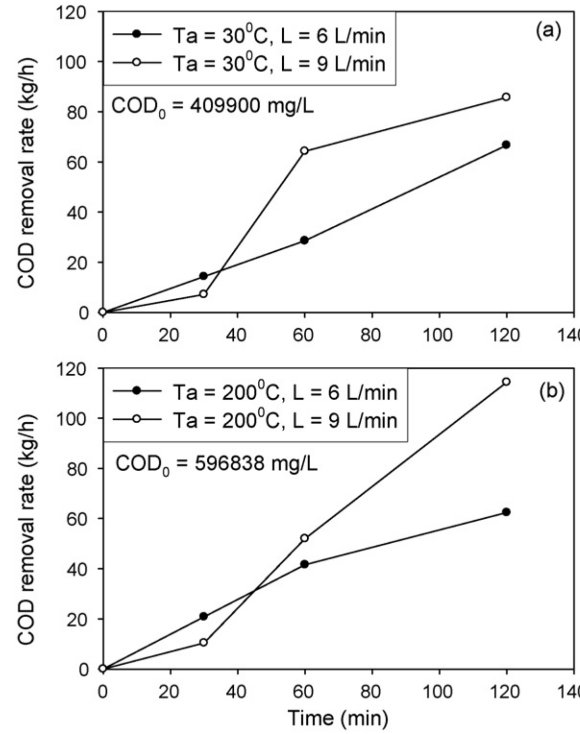


Fig. 6. The effect of water flow rate on the COD removal rate.

where K_La is the volumetric mass transfer coefficient of organic compound i, C_i and C_i^* are the dissolved and saturation concentration of the organic compound, respectively. The volumetric mass transfer coefficient depends on individual diffusion coefficient, gas-liquid contact area, and hydrodynamics in the tower. The saturation concentration or solubility of organic compound depends mainly on the water temperature. During the stripping process, the dissolved organic concentration varies with the position in the tower. Therefore the local organic stripping rate must be integrated over the whole tower to obtain the overall stripping efficiency.

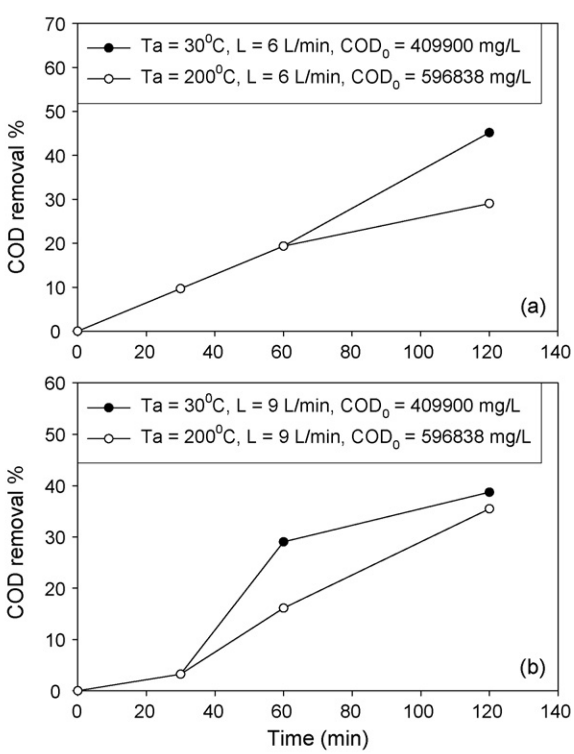


Fig. 5. The effect of stripper inlet gas temperature on the COD removal efficiency.

At a lower inlet gas temperature, the solubilities of the contained organic solvents in the wastewater (C_i^*) are higher; they are not easily stripped by the low-temperature gas. Therefore, a lower water flow rate is needed to provide a longer hydraulic residence time that helps COD to be stripped from the wastewater. At a higher inlet gas temperature, the wastewater in the tower is heated to decrease the solubilities of the organic compounds in the wastewater; thus they become much easier to be stripped from the wastewater. The COD removal efficiency is therefore higher for a higher water flow rate that gives a larger volumetric mass transfer coefficient (K_La).

At first glance of Fig. 5, one might think that the COD removal efficiency should be lower at a higher inlet air temperature. This seems to be contradictory with the relationship between the gas solubility and temperature. Actually, the inlet COD concentrations for the test runs with different inlet gas temperatures are quite different. In order to get a fair comparison, we should use the COD removal rate instead of the removal efficiency.

Fig. 6 shows that the COD removal rates at both low and high inlet gas temperatures increase with the water flow rate. This is reasonable because more COD entering the stripping tower surely results in more COD removal. As shown by Fig. 6a, significant amounts of the organic compounds can be stripped out of the wastewater by 30 °C stripper inlet gas. This fact suggests that the contained organic compounds are semi-volatile and will emit into the atmospheric air under vigorous gas-liquid contact. Therefore, the gas stripping tower helps remove part of COD to alleviate the organic loading to the existing activated sludge process and to reduce the VOC emission from the existing aeration tank. Fig. 7 shows that the COD removal rate at a lower inlet water flow rate slightly decreases with inlet gas temperature, but the COD removal rate at a higher inlet water flow rate increases with inlet gas temperature. This is

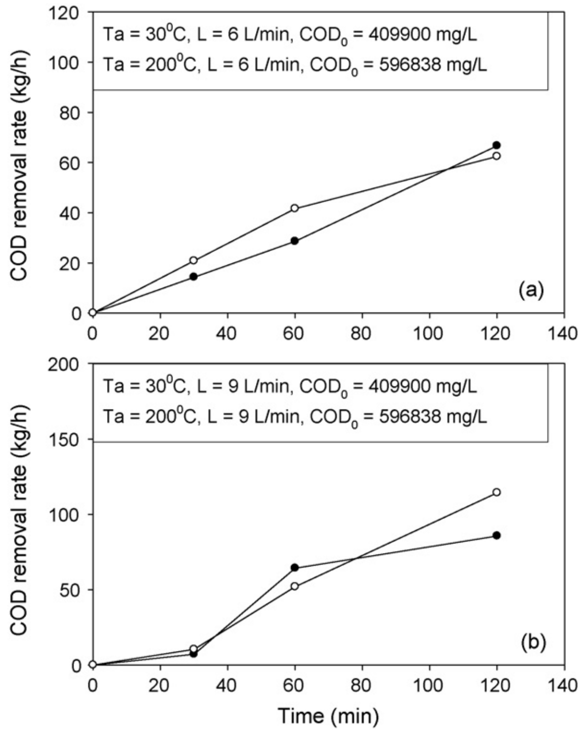


Fig. 7. The effect of stripper inlet gas temperature on the COD removal rate.

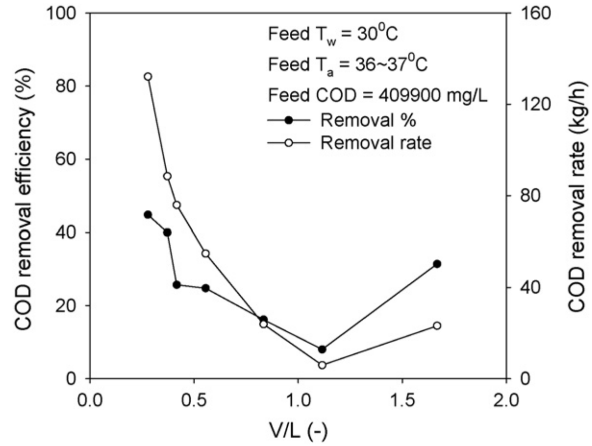


Fig. 8. Effect of gas to liquid flow ratio on the COD removal at a lower stripper inlet gas temperature.

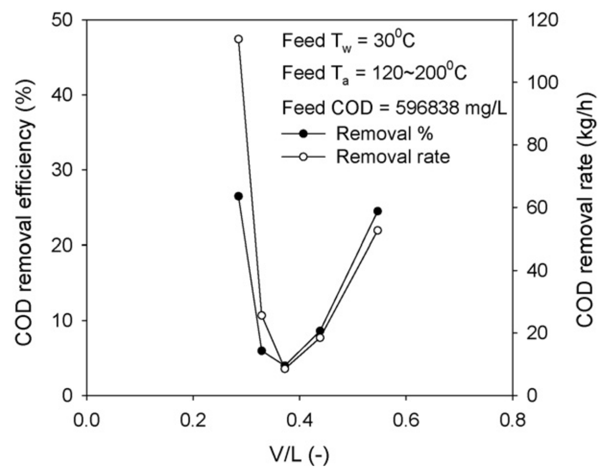


Fig. 9. Effect of gas to liquid flow ratio on the COD removal at a higher stripper inlet gas temperature.

also reasonable because a higher gas temperature results in a higher water temperature and a lower organic compound solubility in the water. The organic stripping rate is thus increased according to Eq. (6).

The inlet gas temperature for the stripping tower depends on the RTO operating conditions. During normal operation with high heat recovery efficiency, the exhaust gas temperature of the RTO is close to the room temperature. In order to obtain a higher exhaust gas temperature of the RTO, the inflow switch time was increased to lower down the heat recovery efficiency [13]. In the above four test runs, the average diesel fuel consumption rate was 1.08 kg/h or 66% (=1 − 1.08/3.15) saving compared with the RTO operation without VOC. Because some fraction of the organic compounds was stripped from the wastewater and became the auxiliary fuel of the RTO, 66% of the fuel can be saved to maintain the combustion chamber temperature between 800 °C and 850 °C.

Another two series of COD stripping tests were conducted at two different COD levels. The experimental data, obtained after reaching steady states are shown in Figs. 8 and 9. In the stripping tests, the feed water temperature and feed COD concentration depend on the PCB manufacturing process; we cannot control these two factors. However, we can manipulate the inlet gas temperature to the stripper, and the gas and water flow rates.

At a lower inlet gas temperature to the stripper (36 ± 1 °C), the effects of gas to liquid mole flow ratio on the COD removal efficiency and removal rate are shown in Fig. 8. Obviously, both the COD removal efficiency and removal rate decrease with increasing gas to liquid flow ratio before V/L = 1.12 at which the removal efficiency and removal rate are the minimum. At a higher inlet gas temperature (120 °C), the COD removal efficiency and the COD removal rate also decreases with the gas to liquid ratio first, reaches a minimum at V/L = 0.37, then increases with the gas to liquid ratio again, as shown in Fig. 9.

Comparing Figs. 8 and 9 leads to realize that the stripping behavior of the high-COD wastewater in combination with the RTO incineration is very complicated. In the future, more studies using the methodology of design of experiment should be conducted to optimize the performance of this combined treatment system.

4. Conclusions

A field study of stripping the organic compounds from the high-COD wastewater streams generated from the PCB manufacturing process was performed. From the experimental results of this study, the following conclusions can be made:

- The heat recovery efficiency of the RTO is very high; a lower inlet gas flow rate gives higher heat recovery efficiency.
- The COD removal rate increases with wastewater flowrate; it also increases with stripper inlet gas temperature.
- The stripping efficiency for the PCB wastewater is less than 45%, but the COD removal rate is very high. Therefore, the stripping tower can serve as an effective pretreatment unit for the high-COD wastewaters to alleviate the organic loading to wastewater treatment facilities and to reduce the VOC emission from aeration tanks.
- The stripped organic compounds can serve as the auxiliary fuel of the RTO to save about 66% of the fuel.
- The combined units of stripping tower and RTO can be used to treat wastewaters with volatile and non-volatile organic compounds and simultaneously recover the heat values of the organic

compounds. The significant RTO fuel saving makes the combined treatment system both technically and economically feasible.

Acknowledgment

The financial and technical support from Taiwan Environmental Engineering Company is greatly appreciated.

References

[1] J.B. Durkee II, Control of industrial cleaning process, in: Management of Industrial Cleaning Technology and Processes, Elsevier, New York, 2006, Chapter 4.
[2] K.B. Schnelle Jr., C.A. Brown, Air Pollution Control Technology Handbook, CRC Press, New York, 2002.
[3] U.S. Environmental Protection Agency Handbook-Control Technologies for Hazardous Air Pollutants, EPA-625-6-91-014, Research Triangle Park, NC, 1991.
[4] M. Bannai, A. Houkabe, M. Furukawa, T. Kashiwagi, A. Akisawa, T. Yoshida, H. Yamada, Development of efficiency-enhanced cogeneration system utilizing high-temperature exhaust-gas from a regenerative thermal oxidizer for waste volatile-organic-compound gases, Appl. Energy 83 (2006) 929–942.
[5] A. Vij, A primer on damper technologies for regenerative thermal oxidizers Understanding the multiple functions that valves serve in common RTO systems, Met. Finish. 104 (2006) 17–22.
[6] M. Amelio, P. Morrone, Numerical evaluation of the energetic performances of structured and random packed beds in regenerative thermal oxidizers, Appl. Therm. Eng. 27 (2007) 762–770.
[7] J.-C. Lou, S.-W. Huang, Treating isopropyl alcohol by a regenerative catalytic oxidizer, Sep. Purif. Technol. 62 (2008) 71–78.
[8] B.-S. Choi, J. Yi, Simulation and optimization on the regenerative thermal oxidation of volatile organic compounds, Chem. Eng. J. 76 (2000) 103–114.
[9] A.S. Gow III, A.S. Gow Jr., Microeconomic theory of chemical production processes: application to aqueous VOC air stripping operations, Adv. Environ. Res. 8 (2004) 267–285.
[10] J.-M. Chern, S.-R. Chou, Volatile organic compound emission rates from mechanical surface aerators: mass-transfer modeling, Ind. Eng. Chem. Res. 38 (1999) 3176–3185.
[11] J.-M. Chern, C.-F. Yu, Volatile organic compound emission rate from diffused aeration systems. 1. mass transfer modeling, Ind. Eng. Chem. Res. 34 (1995) 2634–2643.
[12] C.-C. Hsieh, Removal mechanisms of VOCs in an activated sludge process, J. Hazard. Mater. 79 (2000) 173–187.
[13] L. Jia, Y. Mao, L. Yang, Temperature distribution and heat saturating time of regenerative heat transfer, J. Thermal Sci. 15 (2006) 175–180.