Journal of Hazardous Materials 182 (2010) 39–44

Contents lists available at ScienceDirect

Journal of Hazardous Materials

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

Integration of chemical scrubber with sodium hypochlorite and surfactant for removal of hydrocarbons in cooking oil fume

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ARTICLE INFO

Article history:
Received 30 November 2009
Received in revised form 14 May 2010
Accepted 27 May 2010
Available online 1 June 2010

Keywords:
Odor
Sodium hypochlorite
Automatic control system
Triangle odor bag method

ABSTRACT

There are many types of technologies to control cooking oil fumes (COFs), but current typical technologies, such as electrostatic precipitator, conventional scrubber, catalyst, or condenser, are unable to efficiently remove the odorous materials present in COFs which are the primary cause of odor-complaint cases. There is also a lack of information about using sodium hypochlorite (NaOCl) and surfactants to remove contaminants in COFs, and previous studies lack on-site investigations in restaurants. This study presents a chemical scrubber integrated with an automatic control system (ACS) to treat hydrocarbons (HCs) in COFs, and to monitor non-methane HCs (NMHC) and odor as indicators for its efficiency evaluation. The chemical scrubber effectively treats hydrophobic substances in COFs by combining surfactant and NaOCl under optimal operational conditions with NHMC removal efficiency as high as 85%. The mass transfer coefficient (K_La) of NMHC was enhanced by 50% under the NaOCl and surfactant conditions, as compared to typical wet scrubber. Further, this study establishes the fuzzy equations of the ACS, including the relationship between the removal efficiency and K_La, liquid/gas ratio, pH and C_{NaOCl}.

1. Introduction

Chinese-style cooking always includes stir-frying or deep-frying food in oil, or preheating oil prior to the addition of food and these cooking processes are the most common in Chinese restaurants [1]. Polycyclic aromatic hydrocarbons (PAHs) (from naphthalene, $C_{10}H_8$, to dibenzo(a,h)anthracenes, $C_{22}H_{14}$), which are known to be carcinogenic for people, can be found in cooking oil fumes (COFs) and their concentrations may arise in the kitchens of Chinese homes where housewives prepare food daily [2]. Formaldehyde and acrolein may be found during the high temperature food treatment [3]. The volatile organics compounds (VOCs), including many hydrocarbons (HCs) emitted by COFs [1,4], may produce respiratory symptoms or local irritation in the airways [3]. Consequently, it is not surprising that several epidemiologic studies report that lung cancer in non-smoking Chinese women may be associated with exposure to COFs [5]. Significant indoor hazardous emissions are certainly due in part to COFs [6].

Without installing any applicable or efficacious equipment, the Chinese way of cooking will emit COFs directly into atmosphere. In addition to hazardous compounds emitted, COFs may exhibit a strong, unpleasant odor [2,7], and the exhaust outlet is often close to a sensitive receptor in the vicinity. Thus, high efficiency odor control equipment is also required.

In order to properly treat COFs, electrostatic precipitator, scrubber, catalyst, or condenser technologies have been adopted. However, those technologies usually have the disadvantages associated with cost, dimension, operation, or removal efficiency [8–10]. Nevertheless, wet scrubber is one of the most commonly installed units with absorption being the most dominant mechanism for treating VOCs or odorous waste gases. Unfortunately, the plain wet scrubber may not be enough; the addition of chemical oxidant (e.g., NaOCl) needs to be investigated. Further, the removal efficiency of the absorption process is influenced by the pollutant's solubility in water. One way of enhancing solubility for gaseous compounds that are not easily soluble in water is to add surfactants that can render pollutants in the bulk solution into micelles. Previous studies have shown that surfactants can effectively remove low solubility compounds present in oil or in dense non-aqueous phase liquid [11,12]. Unfortunately, there is a lack of study which involves the use of NaOCl along with surfactant (depurative) simultaneously to remove non-methane HCs (NMHC) in COFs.

Mass transfer coefficient (K_La) is one of the major parameters to design a wet scrubber for the removal of VOCs [13]. The mathematical model developed by Roberts et al. [14] is further adopted to describe the NMHC mass transfer in the gas–liquid system to evaluate its removal efficiency. In this study, the multiple linear regression (MLR) method is used to examine the relationship

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doi:10.1016/j.jhazmat.2010.05.122

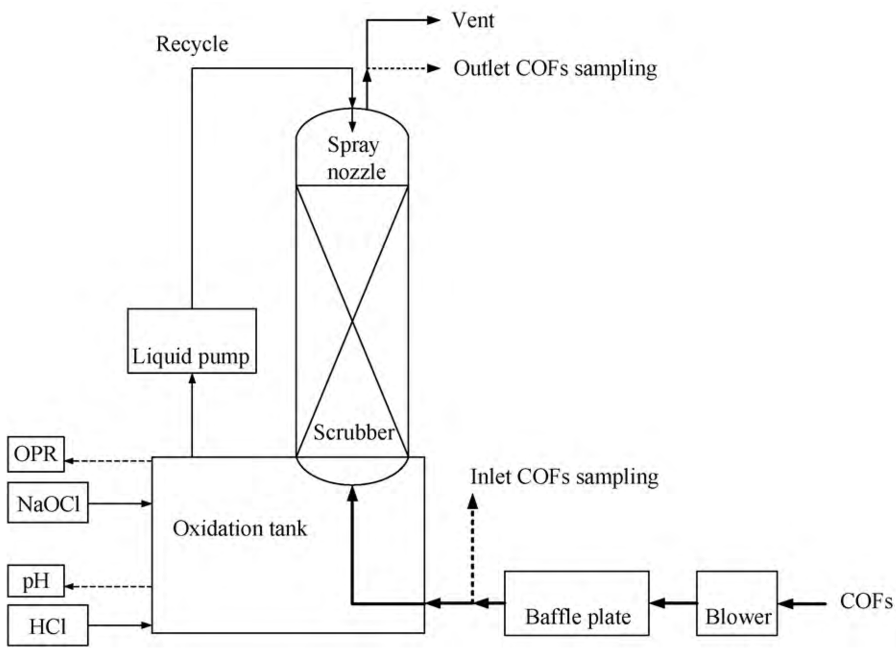

Fig. 1. Installation of a chemical oxidation scrubber.

between dependent variables (K_La and the removal efficiency of NMHC) and independent variables (liquid/gas ratio, pH and C_{NaOCl}). Therefore, one can predict the actual K_La and the removal efficiency of NMHC by using the best regression equations. The result of MLR analysis can be integrated in the automatic control system (ACS) for controlling NMHC emission.

Consequently, the main objectives of this study are, therefore, to explore the feasibility of NMHC removal using NaOCl and a surfactant in a chemical scrubber pilot study and to develop the ACS with easier operation, lower cost and higher acceptance. The above mentioned mass transfer coefficient as well as the utilization of MLR were further investigated to provide better understanding of the overall process.

2. Materials and methods

2.1. Chemicals

The pH was controlled by sulfuric acid (H_2SO_4) (96%) obtained from Panreac. NaOCl (12%) used as the oxidant was obtained from Hung Huei Trading Co., Taiwan. Sodium dodecyl benzene sulfonate ($C_{12}H_{25}SO_3Na$, SDBS) serving as the surfactant and dispersant was purchased from Sunstar Chemical Industrial Co., Taiwan. Methane gas standard (99.0%) was obtained from Scott Specialty Gases.

2.2. Reactor

This study uses a counter-current type scrubber, in which COFs emitted in cooking food process were drawn into the bottom of the reactor and oxidation solution is pumped to the top of packed tower. Fig. 1 shows that the scrubber consists of a baffle plate (45 cm L × 20 cm W × 20 cm H), an absorption scrubber (30 cm Ø × 150 cm H) which have a packing height of 120 cm and an oxidation tank (60 cm H × 80 cm L × 60 cm W) which contained 140 L of water. The packing media are polypropylene Pall rings (Ø 25 mm with the specific surface area of 210 $m^2\ m^{-3}$). The baffle plate can effectively intercept the oil fumes, and then make these fumes to agglomerate in the form of oil drop. Pilot study of the chemical scrubber is conducted within a commercial restaurant.

2.3. Procedures and analytical methods

2.3.1. Operational parameters of chemical scrubber

Table 1 summarizes the cooking conditions of the restaurant used in this study. The test was conducted continuously at least 60 min in each run. The NMHC concentrations generated during the cooking processes ranged from 4 to 39 mg m^{-3} (17 ± 21 mg m^{-3} from 211 samples, Table 1). CH_4 and total HCs (THCs) were analyzed by GC-FID (SHIMADZU GC-14B), with the detection limits of 0.1 and 0.2 ppm, respectively. NMHC concentration was obtained by the difference between THCs and CH_4. The average CH_4 concentration is 1 mg m^{-3} in this study, the NMHC/THCs ratios are from 80 to 98%, which are similar to the results reported by Mugica et al. [4] that range from 80 to 97%.

A series of batch studies were conducted in advance to investigate the optimal parameters for the subsequent study. After establishing the optimal parameters of scrubber, ACS was adopted to make scrubber operation self-control. This study integrated

Table 1
Description of restaurant used in this study.

Cooking conditions	Value or description
Cooking style	Chinese style (including pan-frying, boiling, stir-frying, and deep-frying)
Cooking food	Beef, mutton, pork, fish, vegetables, onion, garlic, and pepper, etc.
Cooking stoves	4
Fuel	LPG
Cooking oil	Soybean salad oil
Seating capacity	90–110
NMHC inlet concentration	17 ± 21 mg m^{-3} (n = 211)

Table 2
Experimental conditions for evaluating the effect of pH on NMHC degradation at C_{NaOCl} 500 ppm and liquid/gas ratio of 8.3 L m^{-3}.

pH	$[NMHC]_{inlet}$ (mg m^{-3})	$[NMHC]_{outlet}$ (mg m^{-3})	Efficiency (%)	Set of NMHC data[a] (n)
5.4–5.5	23 ± 31	4 ± 6	74 ± 17	12
6.0–6.1	10 ± 10	2 ± 2	67 ± 14	10
6.4–6.6	15 ± 18	5 ± 5	65 ± 16	13
7.0–7.2	16 ± 19	6 ± 5	56 ± 18	13
7.5–7.6	24 ± 20	9 ± 7	57 ± 15	12
7.7–8.3	21 ± 26	10 ± 12	44 ± 15	12

[a] The operational time is 60 min for each run.

an ACS on a chip – a so-called system-on-a-chip. The ACS comprised not only one type of closed-loop control system but also an input–output feedback system, which included sensors/probes, a chip and feed units. Fuzzy logic concept was applied to simulate the feedback and control system. The single chip microcomputer was designed to control the optimal parameters via ACS with feedback from sensors. In this study, we can control the scrubber parameters and make the scrubber automatic self-control by using ACS.

2.3.2. *Odor functional test*

To evaluate the intensity of odor, researchers have developed the "triangle odor bag method" which is the most acceptable olfactory sensory test used in Japan since 1972. This test method is an air dilution approach using statistical methods in which "odor index" is measured [15,16]. The triangle odor bag method (NIEA A201.10A) has been used as a standard method to measure offensive odors in Taiwan. In this study, triangle odor bag method was used to measure odors to determine the odor removal performance in the scrubber system.

3. Results and discussion

3.1. *Optimization of operating parameters*

Effects of pH on the degradation of NHMC are summarized in Table 2. The tests in Table 2 are conducted under the same C_{NaOCl} of 500 ppm and the liquid/gas ratio of 8.3 L m^{-3}. The removal efficiencies of NMHC are 74, 67, 65, 56, 57, and 44% for pH levels of 5.5, 6, 6.5, 7, 7.5 and 8, respectively. The results demonstrate that the NMHC removal efficacy increases with decreasing pH, but do not show a significant difference of removal efficacy among pH levels of 6.0 and 6.5; removal efficiencies appear increasing at pH 5.5 and drop significantly as pH > 7. It is identified that formation of free residual chlorine species, HOCl and OCl^-, is the major reaction of chlorination. HOCl has higher oxidation ability than OCl^-. At the lower pH, an aqueous chlorine solution contained higher HOCl and produced free radicals to react with NMHC in COFs. Therefore, the pH of solution should simply be maintained below 6.5 to ensure effective chlorine activity of HOCl. Although the inlet NMHC concentrations of each run in Table 2 are varied with time due to the intermittent emission of the cooking processes, the results indicate that pH maintained at 6.5 has better removal efficacy after evaluating for cost-effectiveness and the pollution problem. There are 13 sets of NMHC data for each run to support the evidence of pH in the solution affecting its removal efficacy.

Effects of various NaOCl concentrations on the degradation of NHMC at the same liquid/gas ratio 8.3 L m^{-3} are summarized in Table 3. First, a blank experiment, which is without adding NaOCl, is carried out and the NMHC removal efficiency is 41%. NaOCl concentrations of 50, 100, 200, 400 and 500 ppm result in the removal efficiencies of 41, 52, 61, 64 and 65%, respectively. The mechanisms of NMHC reacting with NaOCl include the primary and secondary reactions. The primary reaction is that NaOCl directly oxidizes with NMHC, and the secondary reaction is that it produces free radicals that oxidize with NMHC. NaOCl in the aqueous solution forms HOCl, a strong oxidant, which produces free radicals to react with NMHC in COFs. Tap water only dissolves fume substances that does not proceed to chemical reaction or degradation, and saturated absorption phenomenon occurred after long time operation. Adding an oxidant such as NaOC1 to oxidize compounds in COFs is necessary. However, excessive NaOCl does not significantly increase the removal efficacy. Although the inlet NMHC concentrations vary with time due to the dynamic cooking processes, the removal efficiency reached 65% when NaOCl was above 200 ppm. Results show that 200 ppm NaOCl is cost-effective, and at 200 ppm NaOCl (pH = 6.5) exhibits 20% more removal efficiency than tap water alone.

Effects of liquid/gas ratio on the degradation of NHMC are summarized in Table 4 at the same C_{NaOCl} 200 ppm and pH 6.5. Results show that the NMHC removal efficiencies are 47, 61 and 74% for the liquid/gas ratio of 5, 8.3 and 11 L m^{-3}, respectively. An air inflow rate of 3 m^3 min^{-1} with 33 L min^{-1} liquid circulation flow rate makes up a liquid/gas ratio of 11 L m^{-3}. According to "Air Pollution Control and Design for Industry" [17], the cost-effective operational range of air flow velocities, pressure drop for scrubber were 15–90 m min^{-1}, 3.5–10.0 cm Hg, respectively. The experiments conducted in this study contained a low pressure drop, from 0.8 to 2.0 cm Hg. Theoretically, higher liquid/gas ratio increases efficiency, but an excess of the liquid/gas ratio increases pressure drops, energy consumption, flooding and thus operating costs. As the liquid/gas ratio increases from 5 to 11 L m^{-3}, the NMHC removal efficiency could increase from 47 to 74%. We also identify that the operational parameters of liquid/gas ratio may offer better mass transfer between gas and liquid phases, and then the absorption and reaction may become more significant.

According to the above studies, the suitable operating parameters of NaOCl scrubber system at pH 6.5, 200 ppm of C_{NaOCl} and 11 L m^{-3} of liquid/gas ratio are established (Tables 2–4). To advance the removal efficiency, the effects of operational parameters on

Table 3
Experimental conditions for evaluating the effect of NaOCl concentration on NMHC degradation at liquid/gas ratio of 8.3 L m^{-3} and pH 6.5.

C_{NaOCl} (ppm)	$[NMHC]_{inlet}$ (mg m^{-3})	$[NMHC]_{outlet}$ (mg m^{-3})	Efficiency (%)	Set of NMHC data[a] (n)
50	27 ± 26	13 ± 12	41 ± 22	11
100	12 ± 18	4 ± 5	52 ± 20	12
200	32 ± 36	9 ± 10	61 ± 15	11
400	13 ± 11	4 ± 3	64 ± 17	11
500	15 ± 18	5 ± 5	65 ± 16	13

[a] The operational time is 60 min for each run.

Table 4
Experimental conditions for evaluating the effect of liquid/gas on NMHC degradation at C_{NaOCl} 200 ppm and pH 6.5.

Liquid flow rate ($L\,min^{-1}$)[a]	Liquid/gas ratio ($L\,m^{-3}$)	$[NMHC]_{inlet}$ ($mg\,m^{-3}$)	$[NMHC]_{outlet}$ ($mg\,m^{-3}$)	Efficiency (%)	Set of NMHC data[a] (n)
15	5	10 ± 8	5 ± 3	47 ± 18	13
25	8.3	32 ± 36	9 ± 10	61 ± 15	12
33	11	19 ± 13	4 ± 2	74 ± 11	11

[a] The operational time is 60 min for each run.

enhancement factors of K_La should be considered, and it will be discussed in Section 3.3.

3.2. Removal of NMHC under NaOCl and surfactant

3.2.1. Removal of NMHC

The result of removal efficiency showed that added 0.08 mM surfactant to the NaOCl solution increased NMHC removal from 74 to 86% under the optimal parameters of pH = 6.5, 200 ppm of C_{NaOCl} and 11 $L\,m^{-3}$ of liquid/gas ratio as shown in Table 5. We identified that NaOCl changed the arrangement of surfactant in solution. The counter-ion could affect the arrangement of surfactant and could increase the counter-ion binding to the surfactant. [18]. Na^+ (dissociation from NaOCl) used in this study was the major counter-ion of aniotic surfactant. Sodium hypochlorite solutions could be expected to react with fats and oils to form soap. Such saponification would tend to lower the surface tension of sodium hypochlorite solutions on contact with any fats [19]. The presence of a surfactant enhanced the ability of sodium hypochlorite to remove organic material [20]. Extending the operation time from 60 to 150 min, the efficiency of the system remained the same or at least 85%. Apparently, the enhanced performance is due to increased absorbability of non-polar NMHC in COFs with the addition of a small amount of 0.08 mM SDBS.

3.2.2. Odor test to evaluate control efficiency

The NaOCl scrubber was proved to control NMHC effectively in this study, and then odor removal study was conducted at the same parameters. When chemical scrubbers were under the proposed operating parameters (pH 6.5, 200 ppm of C_{NaOCl}, 11 $L\,m^{-3}$ of liquid/gas ratio and 0.08 mM surfactant), the inlet odor index for four runs ranged from 10 to 50. In each case the outlet's odor intensities were lower than 10, which conforms to the regulation's standard of Taiwan EPA. The results indicate that the control technology of NaOCl and surfactant could efficaciously remove odors from COFs.

3.3. Enhancement factor of K_La

The removal efficiency depends not only on the NaOCl concentration but also on the mass transfer coefficient (K_La). The primary operational parameters of the scrubber are liquid/gas ratio and retention time that strongly affect the mass transfer coefficient and removal efficiency [21]. To evaluate the effects of the operating parameters on K_La of NMHC, the enhancement factor (E) was calculated using the following equation.

$$E = \frac{K_La^i}{K_La^0} \quad (1)$$

In which; K_La^0 and K_La^i (min^{-1}) are the mass transfer coefficients under blank conditions and specific operating conditions, respectively. The mechanistic equation developed by Roberts et al. [14] was used to estimate K_La as:

$$-\ln\left(\frac{(C_0 - C)/C_0}{H_C}\right) = \left(\frac{Q_G H_C}{V_L}\right)(1 - e^{-\Phi Z})(t - t_0) \quad (2)$$

In which,

$$\Phi Z = \frac{K_L a V_L}{Q_G H_C} \quad (3)$$

$$V_L = V_P \varepsilon \quad (4)$$

$$V_P = ZA \quad (5)$$

where C_0 and C are inlet and outlet NMHC concentrations ($mg\,m^{-3}$); H_C is the Henry's law coefficient (dimensionless); K_La is the mass transfer coefficient of the NMHC in clean water (s^{-1}); Z is packing height (m); Q_G is the inlet air flow rate ($m^3\,s^{-1}$); Φ is constant (m); $(t - t_0)$ is residence time (s); V_P is the volume of packing zone (m^3); ε is the porosity of packing (%) and A is the cross-sectional area of the reactor (m^2). The major compounds of COFs are HC, including VOCs and PAHs, for which the Henry's law constants H_C range from 2.74×10^{-7} (benzo(a)anthracene, BaA) to 0.77 (2-methylhexane) [22]. The common components of NMHC, comprise benzene, toluene, m/p-xylene and 1,2,4-trimethyl benzene, etc., for which H_C ranges from 0.2 to 0.3 [23]. Here, we assume that the H_C of NMHC is 0.2, Z is 1.2 m; the inlet air flow rate (Q_G) is 3 $m^3\,min^{-1}$; the liquid flow rates range from 15 to 33 $L\,min^{-1}$; the cross-sectional area of absorption scrubber (A) is 0.07 m^2; and the porosity ε of packing (Pall rings) of 90% [24]. We assume that the liquid volume (V_L) in the reactor is 0.5 εV_P for each liquid flow rate of this study. With given C and C_0 values along with different flow rates, the values of K_La can be calculated.

Fig. 2 plots show the factors of pH, C_{NaOCL}, liquid/gas ratio effecting on E of K_La. K_La^0 of the blank was estimated as 31 min^{-1}. The E of K_La increased from 1.1 to 1.4 with the C_{NaOCl} increasing from 50 to 500 ppm. However, the increasing tendency of K_La was insignificant for C_{NaOCl} higher than 100 ppm. The values of E increase with decreasing pH, i.e. E decreased from 1.5 to 1.1 with increasing pH from 5.5 to 8.0, and the values of K_La range from 48 to 33 min^{-1}. This was attributed to the higher oxidation potential at low pH of the NaOCl solution. The values of E increased with increasing of liquid/gas ratio, i.e. from 1.1 to 1.5 with the liquid/gas ratio from 5 to 11 $L\,m^{-3}$. At optimum operating parameters, the value of E increased up to 1.5 and the K_La was 45 min^{-1}. At the suitable operating parameters and with 0.08 mM of surfactant added to the NaOCl solution, the value of E rose to 1.5 and the K_La was 47 min^{-1}. Surfactant, liquid/gas ratio and pH were considered the important factors affecting the NMHC K_La values.

Table 5
Experimental conditions for evaluating the effect of surfactant and operation time on NMHC degradation at C_{NaOCl} 200 ppm, pH 6.5 and liquid/gas ratio of 11 $L\,m^{-3}$.

Surfactant (mM)	Operation time (min)	$[NMHC]_{inlet}$ ($mg\,m^{-3}$)	$[NMHC]_{outlet}$ ($mg\,m^{-3}$)	Efficiency (%)	Set of NMHC data[a] (n)
0	60	19 ± 13	4 ± 2	74 ± 11	11
0.08	60	4 ± 2	1 ± 1	86 ± 8	11
0.08	150	11 ± 11	2 ± 2	85 ± 8	25

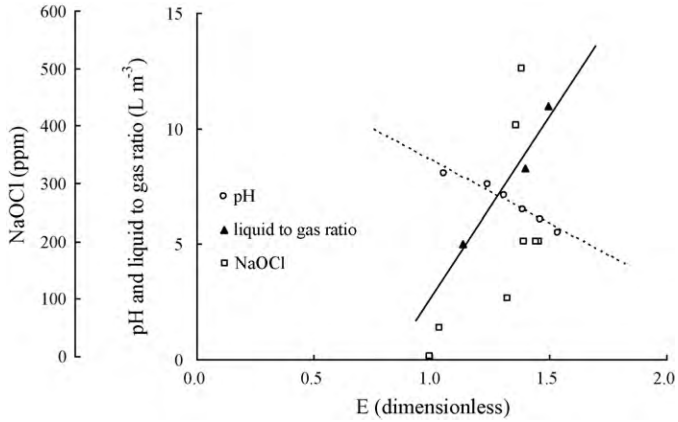

Fig. 2. Variations of E of the K_La under different optimal conditions. Conditions: (○), liquid/gas = 8.3 m^3 min^{-1}, C_{NaOCl} = 500 ppm and pH range from 5.5 to 8.0; (▲), pH = 6.5, C_{NaOCl} = 200 ppm and liquid/gas ratios range from 5 to 11 L m^{-3}; (□), liquid/gas = 8.3 L m^{-3}, pH = 6.5 and C_{NaOCl} from 0 to 500 ppm.

3.4. Fuzzy relational equations for ACS

Since NMHC vary with the cooking process, it can consider that NMHC concentration is a dynamic condition. Thus, the optimization of a continuous chemical scrubber is challenging. If ACS is not used in scrubber system, the NMHC removal efficiency is dropped after the NaOCl is consumed. The objective of ACS is to maintain the optimum operational conditions in pilot-scale. The optimum operational parameters conducted in pilot-scale scrubber are obtained from laboratory-scale under different NaOCl and surfactants inputs, the results shown in Tables 2–4. In the meantime, the relationship between ORP and pH is established via laboratory study. Then, we use ORP and pH sensors to control pH and NaOCl concentration by fuzzy logical system.

3.4.1. ACS for the optimal parameters of scrubber

Since ORP and pH have been demonstrated for determining the chlorine concentration of solution [25,26], we integrate with ACS to measure the variance of C_{NaOCl}. The relationship between C_{NaOCl} and ORP/pH is shown in Fig. 3 (R^2 = 0.95). Using this relationship, the C_{NaOCl} can be controlled at a stable level by ACS, and the standard deviation (SD) of C_{NaOCl} is below 5% (Fig. 4). Thus, with on-line measurements of ORP and pH, the feed concentration of C_{NaOCl} can be easily controlled.

After establishing the scrubber optimal parameters (pH 6.5, 200 ppm of C_{NaOCl} and 11 L m^{-3} of liquid/gas ratio), we used ACS to make scrubber automatic operation. If the ACS received conflicting instructions between C_{NaOCl} and pH, the C_{NaOCl} parameter was designated as the first priority selection. Following adjusting C_{NaOCl} parameter resulting in a stable NaOCl concentration, pH was then adjusted to the set point 6.5. When NaOCl is consumed or below the set point, the ORP and pH sensors send information to ACS, and then ACS controls chemical feeder to add NaOCl in scrubber to maintain ORP or NaOCl at set point. Using ACS and under the scrubber optimal parameters (pH 6.5, 200 ppm of C_{NaOCl} and 11 L m^{-3} of liquid/gas ratio), the NaOCl concentrations are adjusted to maintain 200 ppm (Fig. 4). For the reproducibility tests, as shown in Fig. 5, the average efficiencies are 80 and 79% as the NMHC inlet concentrations varied from 4 ± 2 and 39 ± 29 mg m^{-3}. It is found that the removal efficiency is stable for various inlet NMHC concentrations.

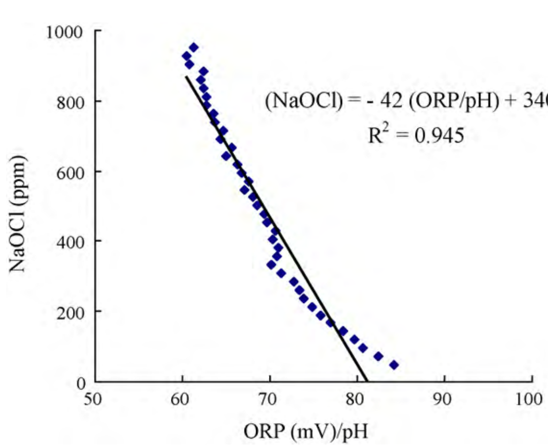

Fig. 3. Relationship between C_{NaOCl} and ORP/pH ratio.

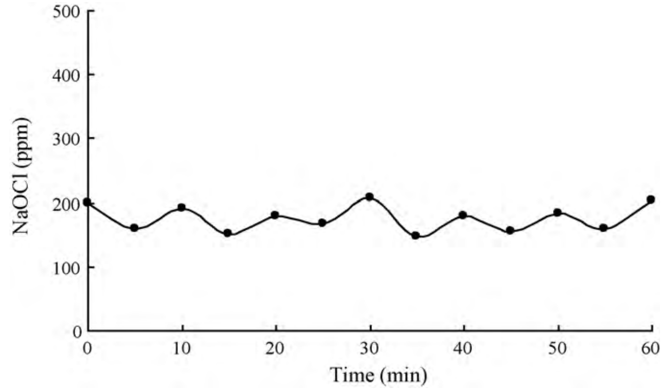

Fig. 4. NaOCl concentration adjustment of ACS for treating NMHC (39 mg m^{-3}) in COFs at the setting parameters of pH = 6.5, 200 ppm of C_{NaOCl} and 11 L m^{-3} of liquid/gas ratio.

3.4.2. Empirical equations for K_La

The MLR method using software SPSS (version 11.5, SPSS Inc.) was derived to examine the relationship between dependent variables (K_La and the removal efficiency of NMHC) and independent variables (liquid/gas ratio, pH and C_{NaOCl}). Table 6 shows the results of the regressions, the lowest sum of squared error (SSE) of expected and observed values and the highest R^2 values of the fitted model are both used to select the best regression equation. All models' p-values are below 0.05, which means that all the models achieved the level of significance. Overall, the equation of $K_La = 56.5 + 1.8\,L/G - 5.2\ \text{pH} + 1 \times 10^{-2}\ C_{NaOCl}$ exhibits the lowest sum of squared errors with relatively higher R^2 value (0.792). It

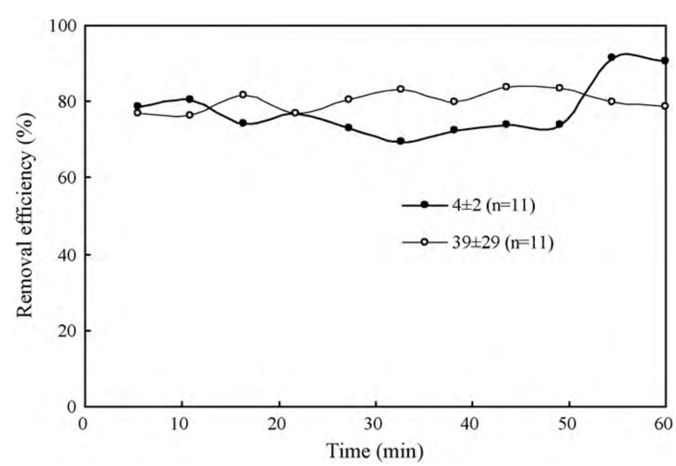

Fig. 5. Independence of inlet NHMC concentrations (4 and 39 mg m^{-3}) on removal efficiency at the ACS conditions of pH = 6.5, 200 ppm of C_{NaOCl} and 11 L m^{-3} of liquid/gas ratio.

Table 6
Prediction models and coefficients of K_La.

Dependent variables	Independent variables				R^2	SSE[a]
	Constant	L/G ($\mathrm{L\,m^{-3}}$)	pH	C_{NaOCl} (ppm)		
K_La	56.5	1.8	−5.2	1×10^{-2}	0.792	69
$1/K_La$	1.4×10^{-2}	-1×10^{-3}	3×10^{-3}	-7.6×10^{-6}	0.746	241
$\sqrt{K_La}$	7.6	1.4×10^{-1}	-4.2×10^{-1}	1×10^{-3}	0.781	76
$1/\sqrt{K_La}$	1.2×10^{-1}	-4×10^{-3}	1.1×10^{-2}	-2.3×10^{-5}	0.758	90
$\ln K_La$	4.1	4.6×10^{-2}	-1.3×10^{-1}	5×10^{-4}	0.770	248
$1/\ln K_La$	2.4×10^{-1}	-3×10^{-3}	1×10^{-2}	-2×10^{-4}	0.757	152
$\log K_La$	1.8	2×10^{-2}	-5.8×10^{-2}	5×10^{-4}	0.770	3981
$1/\log K_La$	5.5×10^{-1}	-8×10^{-3}	2.3×10^{-2}	-4.9×10^{-5}	0.757	77

[a] The sum of squared error (SSE) of K_La.

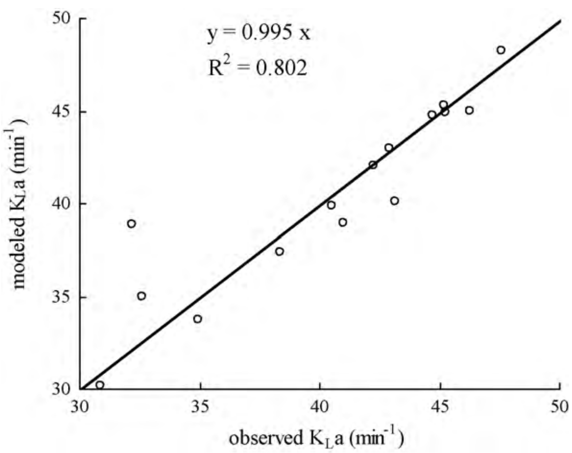

Fig. 6. The modeled and observed K_La of regression model: the root of K_La equation (SSE = 69).

indicates that K_La equation represent an applicable model that one can use to predict the value of K_La; an example is illustrated in Fig. 6 for predicting K_La. Moreover, the regression model can also be incorporated in ACS in future research.

4. Conclusions

This study presented a chemical scrubber integrated with an ACS to treat NMHC in COFs, and the optimal operating parameters for an automatic control chemical scrubber system were validated. Using the ACS, the wet scrubber can be established to operate in the optimum operational conditions and maintain stable NMHC removal efficiency under different inlet NMHC concentrations. The K_La was enhanced up to 150% under the NaOCl and surfactant control system. Using the MLR method to simulate the fuzzy relational equations of ACS, the empirical equations of removal efficiency and K_La derived can be useful in ACS application.

Acknowledgment

The authors gratefully acknowledge the financial support provided by the Republic of China's National Science Council (NSC 94-EPA-Z-224-001).

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