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Ozonation of Odorous Compounds in Gases Emitted from Rubber Processing Industries

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ABSTRACT

This study aimed at the removal of odorous compounds in gases emitted from rubber processing industries. Simulated odorous gas for test was prepared by mixing fresh air and an odorous gas drawn from an oven in which a sample of rubber powder was kept either at 160°C (for a thermal plastic rubber) or 200°C (for a thermal setting rubber). The prepared odorous gas was then premixed with a definite amount of ozone-enriched air and introduced into a contact system. The contact system consists of two sieve-plate columns connected in series and each column has four 1-L chambers. Depending on with or without introducing circulating scrubbing water into the columns, the oxidation reaction could be either wet or dry one.

Results indicate the wet oxidation got better performances than the dry one. The former got 97 and over 90% removal of VOCs (volatile organic compounds) and odorous intensity removal, respectively, with the operation conditions of initial ozone concentration 4.0 ppm, THC (total hydrocarbon) concentrations 6.5–10.3 ppm (methane equivalent), oxidation temperature 37.3°C, gas empty bed retention time (EBRT) 12 s, and liquid/gas rate ratio 0.01 m^3/m^3. With conditions similar to those cited above, odor concentration (dilutions to the threshold, D/T) in the test gas could be reduced from 1,738–3,090 to 31–98 with EBRTs of 11.4–14.5 s. Activated carbon is effective for both physical and chemical removals of residual VOCs, odorous compounds, and ozone in the effluent gas from the ozonation system. Economical analysis indicates that around US$ 0.16 is required for treating 1,000 m^3 of the tested foul gas by the proposed ozonation process.

Keywords: Rubber processing; Ozone oxidation; Odor control; Olfactometry.

INTRODUCTION

Rubber industry uses a broad spectrum of substances such as vulcanization agents, accelerators, activators, and solvents during the manufacture process. In curing and vulcanization of rubber, employers encounter exceed risk of lung cancer, which is believed partially contributed by nitrosamines (Li and Yu, 2002). Epidemiological studies also suggested that exposure of fumes and dusts from rubber processing could be associated with leukemia, lymphoma, and other cancers (IARC, 1982). The genotoxic effects of people engaged in the production of rubber tires were also investigated, and some significant differences were observed between the micronucleus test of the exposed population and those of the control ones (Laffon *et al*., 2006).

Offensive odor was also concerned during the blending and molding process in rubber manufacturing industry. Sakdapipanich and Insom (2006) put effort on the characterizations of the obnoxious odor and the investigation of the odor producing mechanism. They found that the odorous compounds were probably derived from lipid oxidation of unsaturated fatty acids and carbohydrate fermentation. Some of odor-reducing substances like sodium dodecyl sulfate, benzalkonium, chloride, chitosan, carbon black were also used to remove the offensive odor by physical mixing, which was proven to be feasibly useful (Hoven *et al*., 2004).

Odor evokes a wide range of physiological and the emotional reactions of odor vary among people. With instrument measurement, there's no known relationship between the specific gas concentrations in a mixture and its perceived odor (Zahn *et al*., 1997). Nicell (2003) expressed the relationship between population responses (probability of detection, probability of discrimination, and degree of annoyance) and concentration of 6 odorous compounds to serve as the basis for the development of odor impact parameter (Nicell, 2003). Kim and Park (2008) compared the odorant concentration of odor sample from industry with olfactometry and instrumental methods and confirmed that the odorant concentration data by instrument could be used effectively to account for the odor intensity by olfactometry.

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However, olfactometry using trained individuals and standardized procedures to measure odor levels could directly address the odor sensed by human's highly sensitive sense of smell (Jacobson *et al*., 2008).

Advanced oxidation processes such as ozonation and O_3/H_2O_2 have been used worldwide as effective ones to achieve degradation of contaminants in drinking water treatment. Combined with UV, the oxidation processes have been used in destroying carcinogens and hazardous contaminants like gaseous hexamethyl disilazane (HMDS) (Chao *et al*. 2007), gaseous 1,3-butadiene (Chou *et al*., 2005), aqueous refractory compounds such as 2,2,3,3,-tetra-fluoro-propanol (TFP) from CD-R and DVD-R production (Chou and Chang, 2007) and some chlorophenols (Benitez *et al*., 2000). However, removal efficiency of low concentration of indoor volatile organic compounds (VOCs) by ozonation process alone was proven to be low, and the carbon-carbon bonds in unsaturated VOCs may lead to the formation of harmful intermediates (Weschler, 2000). The use of ozone along with porous materials such as activated carbon or zeolite to decompose and adsorb low concentration of VOCs like toluene could achieve the 90% removal efficiency (Chao *et al*., 2007; Kwong *et al*., 2008).

Many countries have reported an increase in public complaints due to odorous emissions. One reason for these problems is the expanding residential development near traditionally agricultural and industrial areas (Mahin, 2001). According to an official data announced by Taiwan EPA (Environmental Protection Administration), the number of odor complaints accounted for around two thirds of air pollution complaints in 2008. The odor complaint number increased by 7.6 times from 1991 to 2008 (Taiwan EPA, 2008; Taiwan EPA, 2009). Odorous emission from rubber processing plants is among the complain causes in Taiwan.

To date, no satisfactory technique can be found for the control of odorous emission from rubber processing plants. In addition, no studies have been focused on the removal of VOCs and odorants in waste gas streams from rubber industry by ozone treatment. In this study, a reactor compose of two sieve-plate towers with a total of 8 reaction chambers was used to decompose VOCs and odor generated from heated rubber powder to 160 and 200°C, respectively. An granular activated carbon (GAC) column was equipped for adsorbing residual ozone, VOCs, and odorous compounds from the reactor effluent. Besides VOC concentration measurement, an olfactometry method directly by human sense was also applied to understand the odor removal efficiency.

MATERIALS AND METHODS

Experimental Setup

Schematic diagram of the experimental system used in this study is shown in Fig. 1. The system consists mainly of an ozone generator (KIA-03-2A, Three Oxygen, Co., Taiwan), an electrical-heated oven, two sieve-plate columns connected in series, two water circulation pumps and the associated pipes, and a granular activated carbon (GAC) column (3 cm i.d. and 10 cmL, packed with 35 g GAC). Each sieve-plate column was partitioned into four 1-L compartments of equal dimension (10 cm sq. × 10 cm height) with 3 sieve plates. Each sieve plate has 64 holes of 1 mm in diameter to enhance the contact of ozone and the influent odorous gas when performing dry-ozonation tests. With wet-ozonation tests, each plate served as a sparger for bubbling the gas through the circulating liquid accumulated on and flowing over the plate and helped to scrub the odorous compounds from the gas. 10 ports were provided for gas sampling.

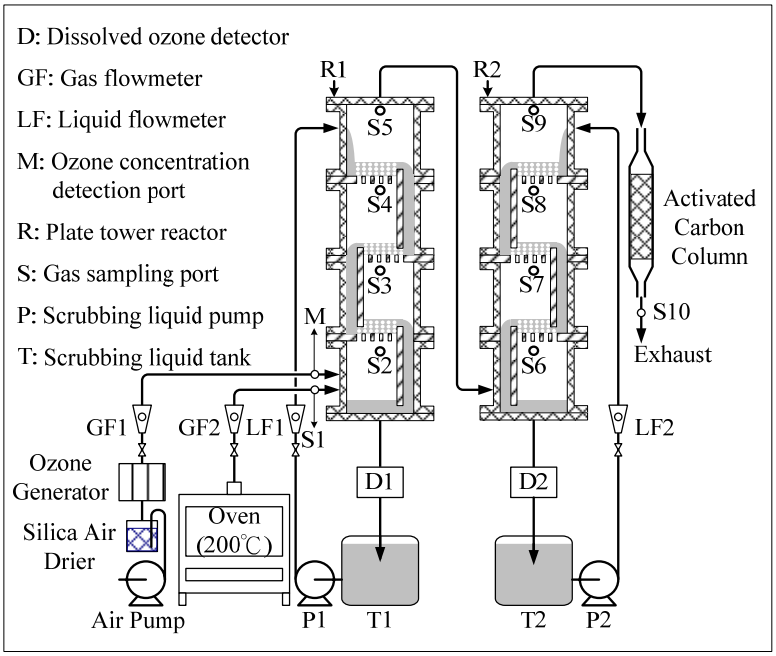

Fig. 1. Schematics of the experimental system.

Materials

In this study, granular (around 0.5 mm in size) samples of a commercial thermal-setting rubber (TSR) and thermoplastic rubber (TPR) were chosen for generation of simulated odorous gases from rubber processing. Odorous gas for test was prepared by mixing fresh air and the odorous gas drawn from the oven in which a sample of rubber powder was kept either at 160°C (processing temperature for the TPR) or at 200°C (vulcanization temperature for the TSR). The prepared odorous gas, when arriving a THC (total hydrocarbon carbon) concentration of 4–5 ppm (methane equivalent), was then premixed with a definite amount of ozone-enriched air and introduced into the reactors.

Operations

Odorous gas generation was operated in batch mode in which a definite amount of the rubber powder (around 1.0 g) was used for a gas generation time of around 90–120 min. Ozonation tests were operated in continuous modes in the gas generation period during which gas samples were taken from the ten ports for determinations of THC and odor intensity.

In this study, two dry oxidation runs using the TSR were performed with ozone doses of 4 and 2.3 ppm, respectively, and a gas flow rate of around 42 L/min. Wet oxidation tests with the TSR were also conducted twice with ozone doses of 4 and 2.3 ppm, respectively, and a gas flow rate of around 35 L/min. For the TPR, only one wet oxidation test was performed with 4 ppm ozone and gas flow rate 42.0 L/min. A liquid to gas ratio (L/G) of 0.01 m^3/m^3 was used for all the wet oxidation experiments.

In addition, two long-term test runs were conducted with ozonation followed by GAC adsorption for accessing the feasibility of post treatment of the gas by the carbon adsorption process.

Analytical

Ozone detection tubes (Gastec No.18L and No.18M, Japan) were used to estimate ozone concentration in gas samples. THC concentrations in gas samples were analyzed with a portable flame ionization detector (FID) with a dual monitor which provides readings of organic and inorganic vapors and meets the requirements of EPA Method 21. A Free Standing Thermometer (YFE, YF-160A Type-K, Taiwan) was used for the temperature measurement.

To examined the VOC compounds of rubber reclaimed working environment and removal performance in this study, the gas samples were analyzed with Gas chromatography (GC) under 200°C for PSR according to EPA Method 524.2 to identify 60 toxic compounds (VOC standard: SUPELCO, environmental standard, EPA 524.2 VOC mix, Catalog NO. 47932). GC (SHIMADZU 14B GC, JAP) with capillary column (SGE BP624, 50 m × 0.53 mm, film thickness 3 μm), carrier gas of nitrogen, carrier gas flow rate of 20.0 mL/min was used in this study, The initial temperature of GC oven of 35°C was maintained for 10 min and increased from 35°C to 180°C at 4 °C/min, and maintained at 180°C for 10 min.

Healthy panelists between 20–40 years old were subjected to the olfactometry test. To prevent the interferences of the decomposition of VOCs by ozone when the olfacometry tests were conducted, the effluent gas passed KI packed column in which ozone was absorbed before entering the sampling bags. The gas samples were then moved to an odorless room for the panelists to conduct olfactometry test. Ranking method was used to evaluate the odor in gas samples taken from the inlet and outlet of scrubber for the odor removal experiments. A scale of 1 to 10 was used, with 0 indicating no odor and 10 representing the odor intensity of the inlet gas. In the olfactometry test, all the gas samples stored in 10 L Tedlar bags were tested within 24 hours without dilution. The same panelists were used during the whole test.

To be more specific, determination of dilution to threshold (D/T) for some gas samples was also used following Standard Method NIEA A20113A of Taiwan EPA. The panelists were selected before the test. In the Standard Method, test papers with phenethyl alcohol (10^{-4} w/w), methyl cyclopentenolone ($10^{-4.5}$ w/w), isovaleric acid (10^{-5} w/w), γ-undecalactone ($10^{-4.5}$ w/w), and skatole (10^{-5} w/w) are used as test odorous chemicals for the olfactometry test, and liquid paraffin as an odorless standard. Panelist who fails to distinguish any of the 5 standards twice would loss the qualification as an olfactometry test panelist. In the formal test, a total of 3 gas sample bags of 1 L volume are used for one odorous sample, in which only one contains the sampled odorous gas. In this method, the tests start with a low dilution ratio of 10, than continue with dilutions of 30, 100, 300, 1000, 3000, and etc., until the dilutions are below the threshold of all the panelists' olfaction. Each gas sample (3 bags with 2 blank and one sample air) is conducted by a panel of 6 panelists. The panelists are asked to smell all the three bags and decide which one contains the real odorous gas sample from low to high dilution ratio until they fail. The highest dilution ratios in which the panelists get the correct answers are the thresholds ratios recorded as "a_1." The dilution ratios in which the panelists start to fail to distinguish the odor are recorded as "a_2." The "personal threshold" is than estimated by the equation:

$$X_i = \frac{\log a_1 + \log a_2}{2} \quad (1)$$

Obtain X by deleting the highest and lowest X_i values and averaging the remaining four X_i, the concentration of odor (Y) could be estimated by the following equation:

$$Y = 10^X \quad (2)$$

RESULTS AND DISCUSSIONS

THC Removal

VOC compounds identified by GC were listed in Table 1, and only 8 and 5 of 60 compounds were observed in the influents and effluents, respectively. Concentrations of

Table 1. Concentrations of VOCs compounds from heated rubber exhaust (200°C) examined by GC.

Compounds	Influent (ppb)	Effluent (ppb)
Vinyl chloride	436	388
1,1-Dichloroethylene	266	83
Isopropylbenzene	298	164
1,2,4-Trichlorobenzene	25	ND
sec-Butylbenzene	85	21
1,3-Dichlorobenzene	27	24
Hexachlorobutadiene	38	ND
Naphthalene	17	ND

ND: Nondetected

vinyl chloride (436 ppb), 1,1-dichloroethylene (266 ppb), and isopropylbenzene (298 ppb) were partially decomposed to the levels of 388, 83, and 164 ppb, while concentrations of 1,2,4-trichlorobenzene, hexachlorobutadiene, and naphthalene were all removed to the level lower than detection limits.

Fig. 2 shows removal efficiency of THC from the heated TSR with an initial ozone concentrations ($[O_3]_o$) of 2.3 and 4.0 ppm without using scrubbing water (dry ozonation). With $[O_3]_o$ of 2.3 ppm and EBRTs of around 7–12 s, influent THC could be removed from around 6–8 ppm (as methane equivalent) to 0–3 ppm and the removal efficiencies were in the range of 60–93%, as shown in Fig. 2(a). However, the results show some instable efficiency at this relatively low initial ozone concentration as compared with that observed using a higher $[O_3]_o$ of 4.0 ppm as shown in Fig. 2(b). The efficiency kept increasing with the EBRT to above 90% within 9.2 seconds under 4.0 ppm of initial ozone with influent THC in the range of 6.5–9.0 ppm at 38.5°C.

Similar to those with dry ozone oxidation, as shown in Fig. 3(a), the THC removal efficiency didn't increase stably with the EBRT in the range of 7–15 s and reached an average level of only 86% with $[O_3]_o$ of 2.6 ppm. A probable reason may be due to the insufficiency of the ozone dosage to effectively remove or oxidize the influent THC in the range of 7.5–11.5 ppm. As shown in Fig. 3(b), the THC removal efficiency with wet ozone oxidation could achieve 100% with $[O_3]_o$ increased to 4.0 ppm at EBRT of 13.7 s for VOCs generated from the heated TSR.

Figs. 2 and 3 show the removal efficiency of THC can reach > 90% around 12 and 14 seconds for 2.6 and 4.0 ppm conditions, respectively. However, it's only around 80% removal efficiency for the odor. The odors of VOCs are not exactly directly proportional to the concentrations of VOCs. Therefore, in some cases the odor removal efficiency was only 80%, while that of THC was 90%. This was because of some residual VOCs had lower olfactory thresholds.

For TPR-generated gas with 4.0 ppm wet ozone oxidation, as shown in Fig. 4, the THC removal efficiency could also achieve 100% at EBRT of > 9 s for influent THC of 3–6 ppm.

Although other study using ozone combined with porous zeolite material (NaX, NaY, and MCM-41) under 50% of humidity was able to remove more than 90% of VOCs, only 20–40% of the removed toluene was due to ozonation (Kwong *et al*., 2008). Combining ozonation with zeolite, over 90% of toluene could keep to be eliminated for several hours (Chao *et al*., 2007). However, the removal efficiency with ozone alone by Boeniger (1995) was observed to be comparatively lower than the results obtained in this study. In the present study, using ozone alone was capable of decomposing more than 90% of VOCs at an initial O_3/THC concentration ratio (ppm/ppm) of around 1/2. The high removal efficiency could be due to the enhancement of THC and O_3 contact when the gas passed trough the sieve holes and the liquid layer and some VOCs were absorbed into the scrubbing liquid and oxidized

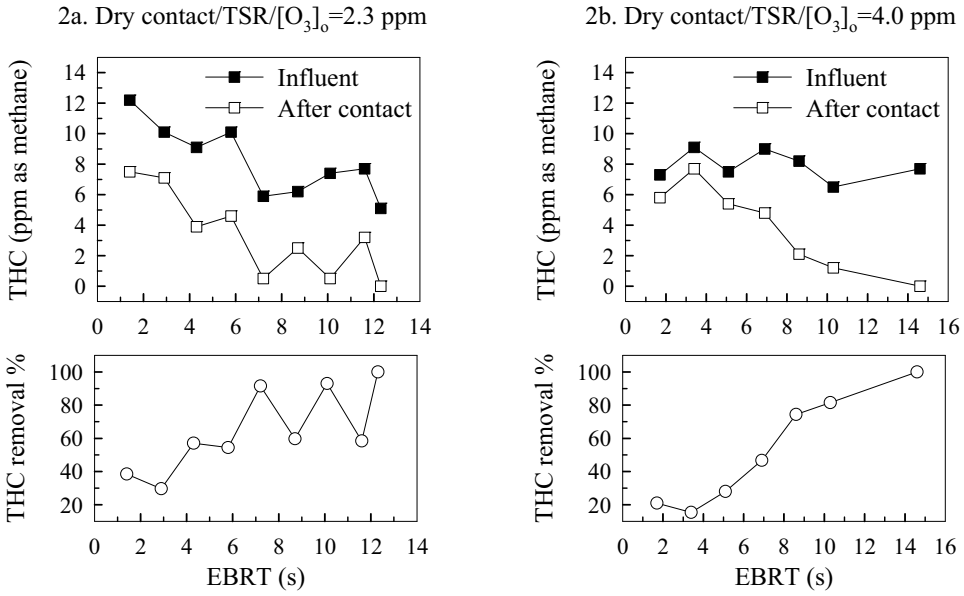

Fig. 2. THC (vented from the heated TSR) concentration and removal efficiency in the dry ozonation test with 2a. $[O_3]_o$ = 2.3 ppm and 2b. $[O_3]_o$ = 4 ppm.

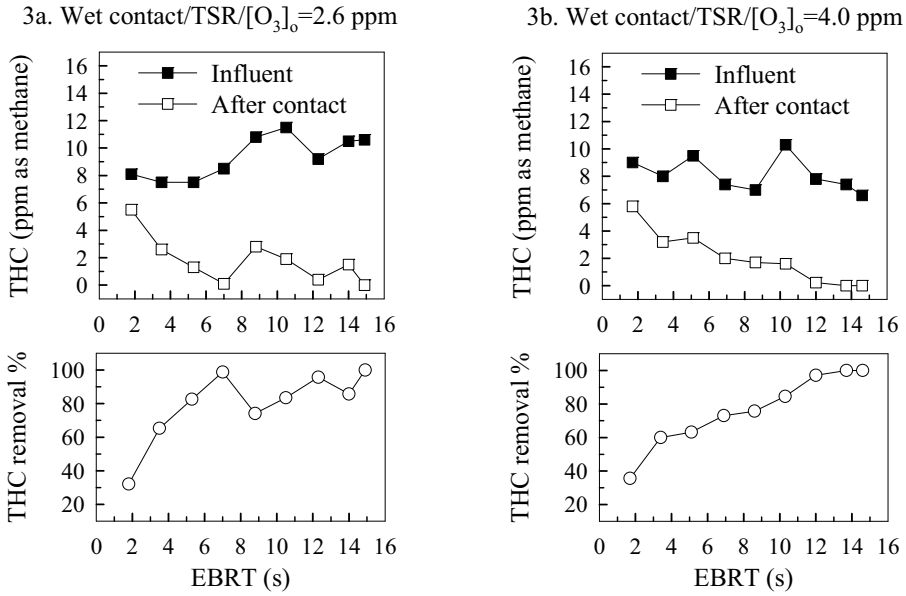

Fig. 3. THC (vented from the heated TSR) concentration and removal efficiency in the wet ozonation test with 3a. $[O_3]_o$ = 2.6 ppm and 3b. $[O_3]_o$ = 4 ppm.

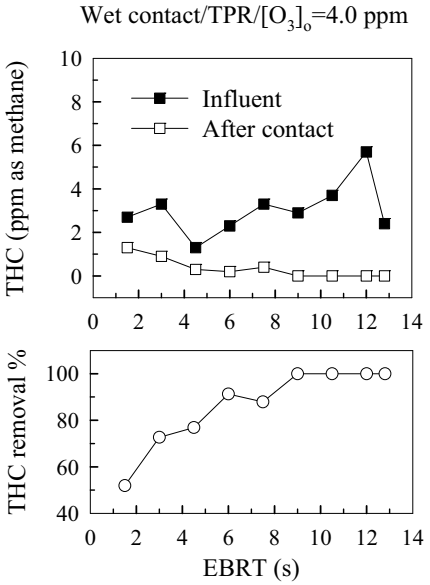

Fig. 4. THC (vented from the heated TPR) concentration and removal efficiency in the wet ozonation test with $[O_3]_o$ = 4 ppm.

therein. In addition, Ozone in the scrubbing water could keep reacting with some dissolved VOCs under continuous operation. In this study, two sieve plate columns were connected in series. Each column was separated into 4 units by 3 sieve plates and some ozone dissolved into the scrubbing water when the gas passed and bubbled through the plate holes and the water flowing over the plates.

VOCs in the scrubbing water were found to be lower than detection limits with COD and GC analysis in the scrubbing water. Therefore, the scrubbing water could be circulated with only some supplementation for the evaporated water.

Reduction of Odor Intensity

With the olfactometry method with scales from 1 to 10, results from the dry ozonation tests indicate that only 80% of odorous intensity in the influent gas could be reduced with initial ozone concentrations of 2.3 and 4.0 ppm and EBRT of > 10 s (Fig. 5(a)). Wet oxidation test of TSR odor with $[O_3]_o$ of 2.6 ppm and EBRT of > 10 s gave a similar result (Fig. 5(b)). The 80% removal means that some residual rubber odor remained in the effluent gas from the pilot reactor and did not meet the odorless requirement set by the authors.

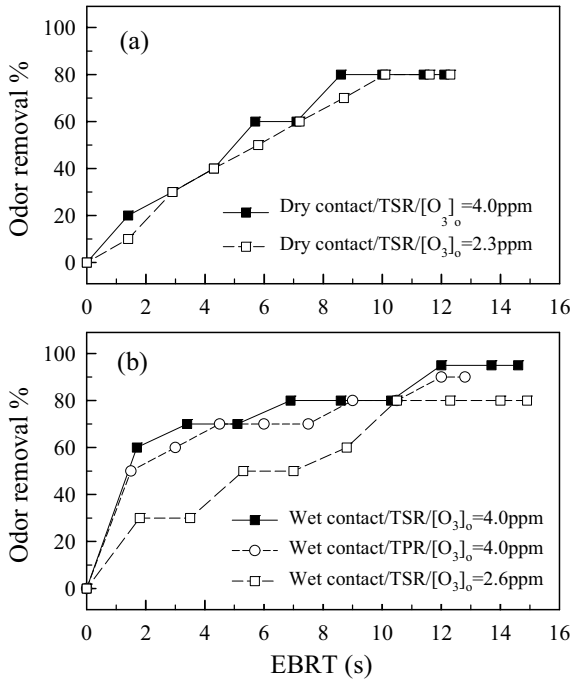

Fig. 5. Odor removal efficiency in the course of ozonation.

As shown in Fig. 5(b) for the wet ozonation tests for odor removal from heated TSR and TPR using $[O_3]_o$ of 4.0 ppm, it shows better removal efficiency than the dry ozonation one. A contact time of over 12 s was required to eliminate almost all the characteristic odors in the effluent and the THC removals were all greater than 95% (Figs. 3(b) and 4). The better performances by the wet ozonation approach might result from highly reactive hydroxyl radicals generated from the reaction of ozone and water.

$$O_3 + H_2O = O_2 + OH\bullet \quad (3)$$

The vibrations of the results of both dry and wet contact of 2.6 ppm is higher than those of 4.0 ppm. The reason might be when the ozone concentration was 2.6 ppm, ozone might be not enough to decompose THC since THC concentrations might alter with time. The vibrations of the results were mainly due to the incomplete reactions and the degree decreased when the ozone concentration was increased to the 4 ppm level.

Long-term Activated Carbon Adsorption Test

Since the role of ozone was taking advantage of the hydroxyl radicals to decompose VOCs into CO_2 and water, granulated activated carbon column behind the scrubber was used for the removal of residual VOCs and ozone from the reactor effluent. THC concentrations at reactor influent and effluent, and the GAC column effluent are shown in Figs. 6(a)–(c) for a long-term test of 1550 min using vented gas from heated TSR and dry ozonation with $[O_3]_o$ = 4 ppm. Gaseous ozone concentrations from effluents of both the reactor and the GAC column are also presented in the figure. Data show that by the dry ozonation process with a contact time of around 12 s, THC in the influent gas could be reduced from an average of 5.35 to 0.87 ppm (84% removal) after the dry contact process, and to 0.29 ppm (95% removal of the influent THC) after passing through the GAC column. The main function of the GAC column is to remove the residual ozone after oxidation. In the present study, an average ozone influent concentration was 4.0 ppm and the effluent from the reactor was 2.75 ppm, which resulted in an average ozone conversion rate of only around 31%. As shown in Fig. 6(d), the GAC was capable of converting almost all the ozone besides removing some VOCs from the influent gas. With the results, the 35 g GAC was enough for treating a total gas flow of around 65 m^3 (0.042 m^3/min × 1550 min = 65.1 m^3). With the data, it needs at most about 0.54 kg GAC for eliminating the residual ozone in 1,000 m^3 of the gas. The cost of GAC (around US$ 1 for 0.54 kg) is moderate to high, alternatively the ozone elimination can easily be replaced by other methods such as reduced by scrubbing with hydrogen peroxide ($O_3 + H_2O_2 = 2O_2 + H_2O$) or by sodium thiosulfate ($O_3 + 2Na_2S_2O_3 + H_2O = O_2 + Na_2S_4O_6 + 2\ NaOH$) solution.

In wet ozonation followed by GAC adsorption test, data shown in Fig. 7(a) display that all VOCs were removed by the ozone dose (4.0 ppm) and no detectable VOCs were presented in the effluent gas from the wet reactor. However, VOCs and ozone started to break through the GAC column at the start of 450 minute as shown in Figs.7(b) and 7(c). The VOCs might be resulted from the

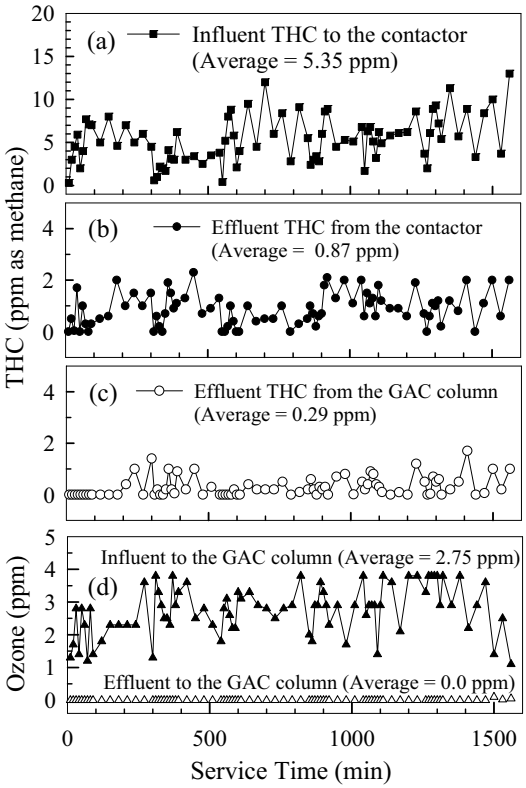

Fig. 6. THC (vented from the heated TSR) and ozone concentrations for the long-term dry-ozonation test with $[O_3]_o$=4 ppm.

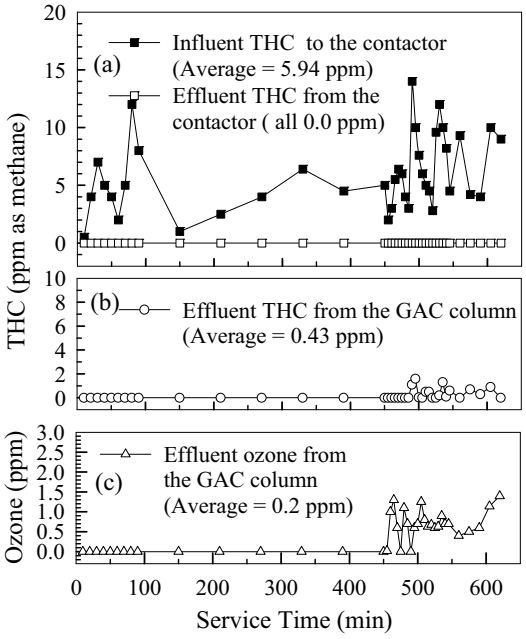

Fig. 7. THC (vented from the heated TSR) and ozone concentrations for the long-term wet-ozonation test with $[O_3]_o$=4 ppm.

desorption of the long-term ones in the GAC column, although no detectable VOCs were measured in the influent of the column. In addition, a reasonable explanation of the shorter breakthrough times for ozone and VOCs in wet ozonation than those in the dry one is that water vapor in the wet gas decreased the adsorption capacity of activated carbon (Qi *et al*., 2000; Kaplan *et al*., 2006). Besides, surface characteristics of GAC were also proven to be affected by the ozone exposure. Surface functional groups of GAC like hydroxyl and carboxyl categories could increase obviously upon ozone exposure (Chiang *et al*., 2002). Valdes *et al*. (2002) also indicated that the higher is the ozone dose that GAC exposed, the higher is the oxidation of the carbon and the greater is the number of acid functional groups present on the carbon surface, especially carboxylic groups. The surface area and micropore volume were found reduced upon high dose of ozone (Valdes *et al*., 2002). Therefore, the activity of GAC could decrease with the ozone exposure time because of the formation of the acidic surface oxygen complexes due to chemisorption of ozone onto GAC (Alvarez *et al*., 2008).

Olfactometry test of the wet ozonztion test indicate that the panelists smelt odor of rubber and ozone at outlet at operation time of 210 and 455 minutes. As for the dry test, the panelists started to smell odor of rubber after 210 minutes of operation and smell ozone at 1410 minutes. To ensure the removal of odor in this adsorption test, gas samples from both dry and wet tests were collected for the dilution to threshold test, and the results are listed in the following section.

Odor Concentrations with the Dilution to Threshold (D/T) Method

Results of the D/T tests for some gas samples are shown in Table 2. For TSR, odor intensity in gas decreased from the original 3,090 to 130 and 98, respectively, when passed through the first reactor (5.7 seconds of EBRT) and the second one (14.5 seconds of EBRT) with wet oxidation by applying 4.0 ppm of initial ozone. For gas generated from the heated TPR, a similar trend was observed that the odor intensity in gas were removed from 1738 to 98 and 31 after 4 and 8 unit volumes (6 and 11.4 seconds of EBRT). This confirmed the fact that ozone had the ability to remove more than 90% of annoying odor from rubber production processes.

D/T tests were observed only for dry ozonation followed by GAC adsorption because of its longer breakthrough time. Gas samples were taken after an operation time of 540 minutes. With dry ozonation alone, the D/T decreased from 4121 to 98, and the GAC further removed the gas odor to a level of 73. All data indicate that this technology, whether with dry or wet ozonation, and with or without followed by GAC adsorption, can reduce D/T of the original gas to a value of less than 100 and meet the regulation of < 1000 set by Taiwan EPA.

Economic Analysis

According to the initial ozone dose of 4.0 ppm (7.84 mg/m^3 @25°C), it requires 7.84 g ozone for the odor removal for 1,000 m^3 of the rubber processing waste gases. By an approximate ozone cost of US $ 20/kg (Hunter and Oyama, 2000), around US $ 0.16 (20/kg × 0.00784 kg/10^3 m^3 = 0.16/10^3 m^3) is required for treating 1,000 m^3 of the tested foul gas by the proposed dry or wet ozonation approach. The ozonation prosess is therefore a cost-effective and energy conservation way for control of odor and VOC emissions from the rubber industrial.

CONCLUSION

Several conclusions can be drawn from the investigations on the ozonation of simulated odorous gas from rubber processing.

1. Wet oxidation got better performances than the dry one. The former got 97 and over 90% removal of VOCs and odorous intensity removal, respectively, with the operation conditions of initial ozone concentration 4.0 ppm, THC concentrations 6.5–10.3 ppm, oxidation temperature 37.3°C, EBRT 12 s, and liquid/gas rate ratio 0.01 m^3/m^3.
2. Odor concentration (D/T) in the test gas could be reduced from 1,738–3,090 to 31–98 with EBRTs of 11.4–14.5 s.
3. Activated carbon is effective for both physical and chemical removals of residual VOCs, odorous compounds, and ozone in the effluent gas from the ozonation system.
4. Around US $ 0.16 is required for treating 1,000 m^3 of the tested foul gas by the proposed ozonation process.

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Table 2. D/T ratios of the tested odorous gases.

Wet ozonation of TSR gas with $[O_3]_o$ = 4 ppm		Wet ozonation of TPR gas with $[O_3]_o$ = 4 ppm		Dry ozonation of TSR gas with $[O_3]_o$ = 4 ppm followed by GAC column	
EBRT (s)	D/T ratio	EBRT (s)	D/T ratio	Sampling location	D/T ratio
0	3090	0	1738	Reactor inlet	4121
5.7	130	6.0	98	GAC column inlet	98
14.5	98	11.4	31	GAC column outlet	73

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