A Review of Some Representative Techniques for Controlling the Indoor Volatile Organic Compounds

Ehsanul Kabir and Ki-Hyun Kim

Department of Farm, Power & Machinery, Bangladesh Agricultural University, Mymensingh, Bangladesh
1)Department of Environment & Energy, Sejong University, Seoul 143-747, Korea

1)Corresponding author. Tel: +82-2-3408-3233, Fax: +82-2-3408-4320, E-mail: khkim@sejong.ac.kr

ABSTRACT

Poor indoor air quality is now worldwide concern due to its adverse impacts on our health and environment. Moreover, these impacts carry a significant burden to the economy. Various technical approaches (e.g., biological, activated carbon fiber (ACF), photocatalytic oxidation (PCO), etc.) have gained popularity in controlling indoor volatile organic compounds (VOCs). This is because removing indoor VOC sources or increasing ventilation rates is often not feasible or economical. This review provides an overview of the various air purification technologies used widely to improve indoor air quality. Although most of these technologies are very useful to remove indoor VOCs, there is no single fully satisfactory method due to their diversity and presence at the low concentration. To achieve technical innovations and the development of specific testing protocols, one should possess a better knowledge on the mechanisms of substrate uptake at VOC concentrations.

Key words: Volatile organic compounds (VOCs), Indoor air quality, Biological treatment, Activated carbon fiber (ACF), Photocatalytic oxidation (PCO)

1. INTRODUCTION

Indoor air quality (IAQ) remains a very important issue today because it can affect human life in many respects (such as health, comfort, satisfaction, and productivity). In the present world, majority of people spend most of their time in indoor environments, e.g., residences, public buildings, and offices (US EPA, 2002; Klepeis et al., 2001; Robinson and Nelson, 1995). With the improvement of living standard and innovation of construction technology, modern airtight buildings are equipped with air-conditioning systems and synthetic materials for decorating and remodeling purposes. The concentration level of indoor air pollutants can increase several hundred times higher than that of outdoor ones (Orwell et al., 2004; Fisk, 2000; Brown, 1997). The prevalence of volatile organic compounds (VOCs) (e.g., formaldehyde, benzene, toluene, xylene, etc.) in indoor environment may trigger immediate or persistent harm to human health (Wolkoff, 2003). The phenomena of sick building syndrome (SBS), building related illness (BRI), or multiple chemical sensitivity (MCS) have been reported frequently in recent years (Liu, 2007; Runeson et al., 2006).

There are a variety of approaches for controlling VOCs in indoor environments such as source control, ventilation, and air cleaning (Lu et al., 2010). Ventilation is commonly the most efficient method but can be disadvantageous for requiring more energy consumption (Khoukhi et al., 2007). At present, air purification remains to be one of the most promising air-cleaning methods to involve diverse control techniques, e.g., adsorption by activated carbon, photocatalytic oxidation (PCO), biological treatment (biofiltration, bioscrubber, vegetation approach, etc.), catalytic oxidation, adsorption, ionization methods (plasma, photocatalytic oxidation, etc.), and other miscellaneous ones (Ao and Lee, 2003; Shen and Ku, 2002). This paper presents a critical review on the potential and limitation of the three air purification technologies (i.e., biological treatment, ACF, and PCO) in light of the widest applicability indoor air quality management.

2. VOCS AND INDOOR AIR QUALITY

Hundreds of VOCs with diverse physical, chemical, and biological properties can be found simultaneously in indoor air. Indoor VOC concentrations are generally higher than outdoor concentrations because VOCs can be released from human activities and a wide variety of indoor sources such as floorings, linoleum, carpets, paints, surface coatings, furniture, etc (Yu and Crump, 1998). These compounds exhibit very large variations in concentration as the composition of the mixture...
replaced from many sources gradually varies through time. However, there are also certain substances of which release depends on punctual human activities or even human breathing (Miekisch et al., 2004; Phillips, 1997; Ekberg, 1994). Indoor VOC concentrations can be controlled further by such variables as the total space volume, the pollutant production and removal rates, air exchange rate with the outside atmosphere, and the outdoor VOC concentrations (Salthammer, 1997).

Furniture coatings were found to release as many as 150 different VOCs (mainly aliphatic and aromatic aldehydes, aromatic hydrocarbons, ketones, etc.) (Salthammer, 1997). As several hundreds contaminants can be found simultaneously, they can result in significant rise in total volatile organic compound (TVOC) levels (Yu and Crump, 1998; Kostiainen, 1995). The effect of such rise on human health hazard is not easy to evaluate, as this generic parameter does not reflect the individual differences in toxicities between indoor air VOCs. However, symptoms (such as headache, dizziness, fatigue, and confusion) have been recorded in subjects exposed to 22 VOCs (Hudnell et al., 1992). In addition, many harmless VOCs can react with oxidants such as ozone, producing highly reactive compounds that can be more harmful than their precursors (Sundell, 1997; Ekberg, 1994). Indoor VOC concentrations can even human breathing (Miekisch et al., 1997). As several hundreds contaminants can be found simultaneously, they can result in significant rise on human health hazard is not easy to evaluate, as this generic parameter does not reflect the individual differences in toxicities between indoor air VOCs. However, symptoms (such as headache, dizziness, fatigue, and confusion) have been recorded in subjects exposed to 22 VOCs (Hudnell et al., 1992).

Most of the biological treatments for indoor pollutants primarily focused on botanical purifiers. In some previous studies, it was found that ornamental indoor plants have the ability to remove harmful VOCs from indoor air (Claudio, 2011; Yang et al., 2009; Tarran et al., 2007; Orwell et al., 2006; Wood et al., 2003). Previous studies revealed that indoor plants could reduce stress and boost performance levels at work because they could soak up harmful air pollutants which may otherwise cause drowsiness, fatigue, and heavy-head feeling (Burchett et al., 2008; Fjeld, 2002). In Table 2 a list of plants suitable for removing individual pollutants is listed with their potential for individual VOC.

In a pioneer study supported by the NASA, Wolverton and coauthors (1984) demonstrated the potential of plants (and their rhizosphere) to remove indoor VOCs in sealed chambers. In their earliest study, these authors found that several plants could remove formaldehyde at 15,500-37,500 ppb, benzene and trichloroethylene

### Table 1. Commonly available VOCs in indoor environment and their sources (Tucker, 2001).

| Order | Chemical | Source                      |
|-------|----------|-----------------------------|
| 1     | Acetone  | Paint, coatings, finishers, paint remover, thinner, caulking |
| 2     | Aliphatic hydrocarbons (octane, decane, undecane hexane, isodecane, mixtures, etc.) | Paint, adhesive, gasoline, combustion sources, liquid process photocopier, carpet, linoleum, caulking compound |
| 3     | Aromatic hydrocarbons (toluene, xylenes, ethylbenzene, benzene) | Combustion sources, paint, adhesive, gasoline, linoleum, wall coating |
| 4     | Chlorinated solvents (dichloromethane or methylene chloride, trichloroethane) | Upholstery and carpet cleaner or protector, paint, paint remover, lacquers, solvents, correction fluid, dry-cleaned clothes |
| 5     | n-Butyl acetate | Acoustic ceiling tile, linoleum, caulking compound |
| 6     | Dichlorobenzene | Carpet, moth crystals, air fresheners |
| 7     | 4-Phenylcyclohexene (4-PC) | Carpet, paint |
| 8     | Terpenes (limonene, a-pinene) | Deodorizers, cleaning agents, polishes, fabrics, fabric softener, cigarettes |

### Table 2. VOC removal efficiency by indoor plants over 6 h duration (Yang et al., 2009).

| Order | Plant                          | Benzene | Toluene | Octane | Trichloroethylene (TCE) | α-Pinene | Total     |
|-------|--------------------------------|---------|---------|--------|-------------------------|----------|-----------|
| 1     | Hemigraphis alternata          | 5.54±0.29 | 9.63±0.94 | 5.58±0.68 | 11.1±0.99 | 12.2±1.61 | 44.0±2.98 |
| 2     | Hedera helix                   | 3.63±0.33 | 8.25±0.64 | 5.10±0.49 | 8.07±0.77 | 13.3±0.95 | 38.3±3.17 |
| 3     | Tradescantia pallida          | 3.86±0.58 | 9.10±1.12 | 2.76±1.08 | 7.95±1.20 | 10.5±1.78 | 34.1±5.52 |
| 4     | Asparagus densiflorus         | 2.65±0.24 | 7.44±0.28 | 3.76±0.64 | 6.69±0.49 | 11.4±0.78 | 31.9±2.40 |
| 5     | Hoya carnosa                  | 2.21±0.21 | 5.81±0.67 | 3.80±0.62 | 5.79±0.75 | 8.48±1.17 | 26.1±3.40 |
| 6     | Ficus benjamina               | 1.66±0.07 | 5.06±0.19 | 3.98±0.19 | 4.74±0.15 | 4.68±0.40 | 24.1±0.85 |
| 7     | Polyscias fruticosa           | 1.53±0.08 | 4.29±0.04 | 3.43±0.08 | 3.98±0.16 | 8.30±0.12 | 21.5±0.42 |
| 8     | Fritillaria argyrophylla      | 2.74±0.28 | 5.09±0.23 | 1.77±0.25 | 6.15±0.36 | 4.30±0.39 | 20.1±1.46 |
at 102-686 ppb in 24 h (Wolverton et al., 1989; Wolverton et al., 1984). Through their research, Wolverton and Wolverton (1993) also found that the air-cleaning capacity of houseplants can be improved exponentially by increasing air circulation to the roots of the plants, where symbiotic microorganisms can help make the bioavailable substances culled. Orwell et al. (2004) investigated the potential of indoor plants for removing benzene in sealed chamber (0.216 m³) and found that microorganisms of the plant rhizosphere were mainly responsible for its removal (12-25 ppm d⁻¹). These results were obtained at high initial benzene concentrations (25-51 ppm). They observed that benzene removal rate increased linearly with the dosed concentration, suggesting that the system should be inefficient under typical indoor air conditions. The same team in another experiment demonstrated that plants significantly reduced toluene and xylene at indoor air concentrations of 203-235 ppb (Orwell et al., 2006). Tarroman et al. (2007) found that indoor-plants could reliably reduce TVOC by 75% in their laboratory studies (with nine species) and field studies (in 60 offices). In a previous study, it was observed that three plants in a real office of average area 13 m² (volume 32.5 m³) were more than enough to reduce TVOC by up to over 75% with or without air-conditioning (Wood et al., 2006). Nevertheless, studies have demonstrated that it was the microorganisms at the root-zone of the plants which were the primary removal agents of the VOCs (Orwell et al., 2006). Therefore, if the polluted air is introduced into a plant root system and degraded by the microorganisms, the removal capacity of the plant can be improved further than the potted plant with leaf effect only. Studies also showed that plants grown in hydroculture were more effective in removing VOCs than soil-grown plants, primarily due to increased air flow to root microbes (Burchett, 2005). Hydroculture also has many other added benefits such as reducing the incidence of mold and mildew as the surface remains dry (Burchett, 2005).

Many parameters such as the interfacial areas, the moisture content, and the hydrophobicity of the selected biomass can influence pollutant removal in biological purifiers. Sandhu (2007) suggested that bacteria growing on plant leaves could also contribute to VOC biodegradation. Direct pollutant accumulation or degradation by plants has however been demonstrated to occur during phytoremediation of contaminated soils (Newman and Reynolds, 2004). The ability of plant leaves to directly take up and remove pollutants for air treatment is still however open for debate (Schäffner et al., 2002; Schmitz et al., 2000; Wolverton et al., 1984).

Just placing a few plants inside a building will not solve a serious IAQ problem, while ventilation alone cannot take such role either (Girman et al., 2009). Several factors should be considered concurrently to optimize the use of plants for the improvement of indoor quality. Note that the output of chamber studies can be meaningful, if concentrations selected for such tests can actually represent those present in actual indoor environments. Moreover, chamber study results should be reported as mass of pollutant removed per hour per plant mass to facilitate direct comparisons with other removal methods. The schematic of a sample chamber test set-up is shown in Fig. 1.

3.2 Activated Carbon Fiber (ACF)

Adsorption process is one of the most efficient and safest processes to remove VOCs from indoor air (Bastani et al., 2010; Benne and Griffith, 2009). Activated carbon fiber (ACF) filter is a promising technology for removing VOCs from indoor air because of its regen-

![Fig. 1. Schematic diagram of the chamber test setup by indoor plants: (A) top-view and (B) side-view.](image-url)
erative properties (Huang et al., 2010; Yao et al., 2009a; Haghhighat et al., 2008; Das et al., 2004). ACF is generally made from rayon, polyacrylonitrile (PAN), or phenolic resin (Huang et al., 2010). The fibers are woven into a fabric and then activated in steam or CO$_2$ at high temperatures (e.g., 800°C). The narrow pore size contributes to the large adsorption capacity of ACF. ACF also has large surface areas, which range from 1000 to 2400 m$^2$g$^{-1}$, with a typical value of 1800 m$^2$g$^{-1}$ (Huang et al., 2010; Lorimier et al., 2005; Das et al., 2004). ACF does not contain impurities that can catalyze oxidative reactions and lead to decomposition of the adsorbate within the adsorbent (Das et al., 2004). Accordingly to the previous studies, ACF filters are very good VOC adsorbents, to show improved performance relative to granular activated carbon, zeolites, and silica gel under identical operation conditions (Huang et al., 2010; Das et al., 2004; Liu, 1992).

To utilize the ACF filter more efficiently, it can require regeneration step in which the adsorbed VOCs must be periodically desorbed from the filter (and exhausted outdoors). There are three different regeneration methods for the filters ((i) using outdoor air under ambient conditions, (ii) with humidified air, and (iii) with heated air). Among these options, the best performance was achieved by regenerating it for 15 minutes once every 12 hours by employing heated air up to 150°C (Dombrowski et al., 2004). The air flow during regeneration was maintained as only 1 percent of the total airflow during the 12-hour period of air cleaning (Dombrowski et al., 2004). Hence, only a very small amount of air needs to be heated, regarding the small amount of energy for regeneration.

Table 3. Percent removal efficiency and air cleaning effectiveness ratio for ACF with different regeneration techniques (VOC source emission rate=6.4 ppb h$^{-1}$ for each compound).

| VOCs     | Conditions          | Percent removal efficiency | VOC cleaning ratio ($R_i$) | Reference          |
|----------|---------------------|----------------------------|---------------------------|--------------------|
| Benzene  | Heated outdoor      | 60                         | 0.26                      | Sidheswaran et al., 2012 |
| 1-Butanol| Unheated outdoor   | 46                         | 0.33                      | Yao et al., 2009b   |
| Toluene  | air regeneration    | 60                         | 0.26                      | Lorimier et al., 2005 |
| o-Xylene | and outdoor air     | 56                         | 0.28                      | Yao et al., 2009b   |
| Limonene | ventilation rate    | 54                         | 0.29                      | Sidheswaran et al., 2012 |
| Undecane | of 0.4 h$^{-1}$     | 54                         | 0.29                      | Sidheswaran et al., 2012 |
| Formaldehyde |                | 16                         | 0.72                      | Yao et al., 2009b   |
| Benzene  | Heated outdoor      | 60                         | 0.36                      | Sidheswaran et al., 2012 |
| 1-Butanol| Unheated outdoor   | 46                         | 0.44                      | Yao et al., 2009b   |
| Toluene  | air regeneration    | 65                         | 0.33                      | Lorimier et al., 2005 |
| o-Xylene | and outdoor air     | 56                         | 0.30                      | Yao et al., 2009b   |
| Limonene | ventilation rate    | 54                         | 0.30                      | Sidheswaran et al., 2012 |
| Undecane | of 0.6 h$^{-1}$     | 76                         | 0.29                      | Sidheswaran et al., 2012 |
| Formaldehyde |                | 24                         | 0.71                      | Yao et al., 2009b   |

Although activated carbon filters can remove a broad range of VOCs from indoor air, their capacity to adsorb formaldehyde is relatively low (Fisk, 2007). Huang et al. (2010) studied the performance of ACF with a mixture of VOC (a molecular weight of 30 to 156 and boiling point of $-21$ to 196°C). The time-averaged removal efficiency of all except formaldehyde was above 70 percent, while that of formaldehyde was approximately 20 percent. However, using a double layer, ACF cloth, Huang et al. (2010) found such efficiency can be raised to 40 percent, while those of others also exceeded 90 percent.

ACF media has a long adsorption lifetime and can
be used effectively to remove indoor VOCs with periodic regeneration (Ramirez et al., 2005). The isotherm data obtained for the ACF showed that it took about 100 hours to fully saturate the ACF media with realistic concentrations of indoor VOCs (Sidheswaran et al., 2011). Yao et al. (2009b) suggested that short periods of DC electrical heating (150 to 200°C) of the carbon fibers was a promising option for periodically regenerating ACF. As an alternative to DC heating of the ACF media, regeneration might be accomplished by passing heated air through the ACF media (Sidheswaran et al., 2011). During the heating period, air is supplied through the ACF at a low flow rate to be exhausted outdoors. This process can also re-transport the desorbed VOCs vented from the building. As an alternative to DC heating (of the ACF media), regeneration can be accomplished by passing heated air through the ACF media (Ramirez et al., 2005). Moreover, results from periodic adsorption and desorption experiments showed that the ACF media should be easily regenerated after a 12 or 24 hour period of air cleaning (Sidheswaran et al., 2011).

Modeling indicates that the combination of ACF air cleaning and a 50 percent reduction in ventilation can decrease indoor concentrations of VOCs by 60 to 80 percent, while reducing formaldehyde by 12 to 40 percent (Yao et al., 2009b). Thus, the system can suppress exposures to VOCs and formaldehyde, while simultaneously reducing the ventilation (up to half) to save energy. However, it is essential to optimize parameters such as duration and frequency of regeneration cycles, the air flow rate, and temperature. The ACF system must be energy efficient compared to the traditional ventilation process, while still capable of providing sufficient regeneration during periods of building occupancy (Sidheswaran et al., 2011). Nevertheless, most previous studies of ACF to remove indoor VOCs were limited to high concentrations of VOCs (ppm) with a few limited target compounds (Benne and Griffith, 2009). However, to allow a reduction in ventilation rates, an air cleaning system needs to be effective in removing a broad spectrum of VOCs that are present simultaneously in the indoor air at low ppb-level concentrations. Table 3 shows the percent removal efficiency of different VOCs and the corresponding air cleaning ration ($R_i$) values for different conditions. Here, $i$ is defined as the ratio of the indoor VOC concentration with an air handling unit with the ACF filter installed in the system to the indoor VOC concentration with an air handling unit without the ACF filter. It was observed that in both the low (0.4 h$^{-1}$) and high (0.6 h$^{-1}$) ventilation rates, the system equipped with heated ACF filter bed performed better than the system without it. It was also observed that cases in which ACF was regenerated by heating have lower $R_i$ values than the corresponding cases in which ACF was regenerated with unheated outdoor air. This suggests that the heated regeneration method should improve ACF VOC-removal performance compared to the unheated outdoor air regeneration method. The schematic diagram of the experimental set-up used for the regeneration of ACF is shown in Fig. 2. The regeneration of ACF was carried out by electrical heating and nitrogen flow. A complete regeneration of ACF typically requires temperature of ~150°C and regeneration time of 60-75 min. The temperature is monitored by a thermocouple fixed at the surface of the ACF sample. The concentration of the exit gas from the reactor can be measured with the help of a gas chromatography (GC) using flame ionization detector (FID).

3.3 Photocatalytic Oxidation (PCO)

Photocatalytic oxidation (PCO) is a promising technology for the remediation of organic pollutants which has been under development for a number of years (Tomkins et al., 2005; Zhao and Yang, 2003). It is a cost-effective technology for VOCs removal compared with adsorption, biofiltration, or thermal catalysis (Dvoranova et al., 2002; Kim et al., 2002). PCO process harnesses radiant energy from natural (or artificial) light sources with heterogeneous catalyst to degrade the organic pollutants into their mineral components (Li et al., 2005a; Ao et al., 2004; Hoffmann, 1995). Titanium dioxide (TiO$_2$) is the most widely used.
catalyst for the photocatalytic reaction (Wang et al., 2007). Other semiconductors (such as ZnO, ZnS, CdS, Fe₂O₃, and SnO₂) are also commonly used catalysts (Wang et al., 2007). The PCO process creates hydroxyl radicals and super-oxide ions, which are highly reactive electrons (Pichat et al., 2000). These highly reactive electrons aggressively combine with the air pollutants (e.g., VOCs). Once bound together, the chemical reaction takes place between the super-charged ion and the pollutant to effectively oxidize (or burn) the pollutant. This breaks the pollutants down into harmless components (carbon dioxide and water molecules), making the air more purified (Hodgson et al., 2007).

Wang et al. (2007) supplied VOCs contaminated air over a titanium dioxide (TiO₂) catalyst at room temperature, while illuminating with a black lamp. These authors found that over 95% of the VOCs were converted to carbon dioxide and water. At 70°C, the reaction rates were three to four times faster than at room temperature. They also revealed that a platinum-doped (Pt/TiO₂) catalyst could achieve even higher reaction rates without producing any detectable carbon monoxide (Wang et al., 2007). Performance of the Pt/TiO₂ catalyst was improved further with increasing temperature with both thermal and photocatalytic effects to contribute to the compound destruction (Wang et al., 2007). The best performance was obtained at 150°C which was the highest temperature selected for their testing (Wang et al., 2007). Addition of ozone to the air stream also increased the process efficiency, but the use of ozone can raise safety and cost issues. Stevens et al. (1998) reported the operational characteristics of four PCO reactor designs using P25 TiO₂ for the oxidative destruction of formaldehyde, acetaldehyde, and acetone. Their result showed that photodegradation of acetaldehyde was lower than that for formaldehyde and acetone. PCO of the formaldehyde and acetone was nearly 100% for all reactor designs (Stevens et al., 1998). Cao et al. (2000) investigated the nanoscale TiO₂ catalysts for the photocatalytic oxidation of toluene. They found that the nanoscale TiO₂ samples were highly active for the photodegradation of toluene. However, the use of platinum loaded on TiO₂ could facilitate the removal of poisonous intermediates from the deactivated TiO₂ surface, while resulting in lower oxidation rates of toluene (Cao et al., 2000). Pichat et al. (2000) employed a TiO₂ coated fiber glass mesh composed of anatase TiO₂ and SiO₂ for photocatalytic oxidation of benzene, toluene, and xylenes (BTEX) in indoor air. According to their study the average concentrations of BTEX were indeed reduced by a factor of 2-3 in an ordinary non-airtight room.

Li et al. (2005b) reported that the photocatalytic efficiency of the TiO₂ catalysts with the lanthanide ion doping can exhibit remarkably enhanced removal efficiency for BTEX. The 1.2% Ln³⁺-TiO₂ catalysts achieved the highest photocatalytic activity. The enhanced photo degradation of BTEX is possibly due to the improved adsorption ability and the enhanced electron-hole pairs separation due to the presence of Ti³⁺ on the surface of Ln³⁺-TiO₂ catalysts and the electron transfer between the conduction band/defect level and lanthanide crystal field state (Li et al., 2005b). Shiraishi et al. (2005) developed a high-performance photocatalytic reactor with a parallel array of nine light sources for photocatalytic decomposition. These authors found that this photocatalytic reactor can rapidly decompose HCHO toward zero concentration. It was recognized that at high humidity levels, water vapor competed with TiO₂ for adsorption sites which decreased the rate of PCO.

To improve this situation, Ao and Lee (2003) developed an activated carbon (AC) filter immobilised with TiO₂ (TiO₂/AC). The results indicated that the removal efficiency of TiO₂/AC was seven times higher than TiO₂ under high humidity levels. Shen and Ku (2002) found that the addition of ozone into the TiO₂/UV/TCE system with 254 or 365 nm UV lamps reduced the removal of TCE, possibly because excessive ozone molecules could scavenge hydroxyl radicals produced from the excitation of TiO₂ by UV radiation. Kirchnerova et al. (2005) explored the photocatalytic activities of two commercial TiO₂ catalysts, Degussa P25 and Hombicat UV100, for n-butanol decomposition under visible light. They found that Degussa P25 was more active than Hombicat UV100. One new approach to produce visible-light activated TiO₂ photocatalysts is by doping with anions such as N³⁻, C⁴⁻, S⁴⁻ or halides (F⁻, Cl⁻, Br⁻, and I⁻) (Belver et al., 2006). It was suggested that these species substitute the oxygen lattice on TiO₂ and lead to a band gap narrowing which may ultimately lead to high visible absorption.

Yu et al. (2009) found that only the surface area of the reactor influenced the PCO rate sensitively, while the UV light had a better PCO effect than that of visible light. Hence, the consumption condition of the UV light in indoor will be an important issue of further studies. Yu and Brouwers (2009) conducted photocatalytic oxidation experiments at room temperature under visible light and demonstrated its convenience for the indoor air purification. Besides the photocatalyst, no other materials are required for the degradation of indoor air pollutants. However, hexamethyldisilazane cannot be treated effectively using PCO techniques. Because of silicon containing reaction products, the catalyst is deactivated minutes after hexamethyldisilazan contact (Wang et al., 2007). The catalyst can hence...
be reactivated partially by flushing with water or other solvents. Nonetheless, the speed with which deactivation takes place renders any sort of regeneration process impractical (Wang et al., 2007).

Table 4 summarizes the results on various photocatalytic oxidations for indoor VOCs. The schematic diagram of the PCO setup for indoor air assessment is also plotted in Fig. 3. This experimental setup is composed of the reactor, gas supply, analyzer, parameters controller, etc. A known amount of photocatalyst (e.g., P25 TiO₂) is coated onto the inner wall of the glass tube. Exact photon output from the lamp is measured periodically with an ultraviolet (UV) spectrometer. The photo reactor can then be incorporated into a test system that allows researchers to vary flow rate, VOC air concentration, humidity, and temperature.

4. CONCLUSIONS

This review presents an overview of the various technical approaches (e.g., biological, ACF, and PCO) currently available for indoor air treatment. Nonetheless, there is yet no single fully satisfactory method for VOC removal from indoor air due to the difficulties linked to the very low concentration, diversity, and variability of VOCs in the indoor environment. Although the above mentioned methods have shown certain potential for the removal of VOC, the specific characteristics of indoor air pollutants and the indoor environment can yield numerous challenges. In particular, new methods must be developed to inoculate, express, and maintain a suitable and diverse catabolic ability under the conditions of trace substrate concentration. In addition, the methods for the treatment of indoor air must be able to purify a large amount of air in spatially confined environments with minimal nuisances. This requires technical innovations, the development of specific testing protocols, and a better understanding of
the activities and the mechanisms of VOC uptake by different substrates.

ACKNOWLEDGEMENT

This study was supported by a National Research Foundation of Korea (NRF) grant funded by the Ministry of Education, Science and Technology (MEST) (No. 2010-0007876).

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(Received 5 June 2012, revised 30 July 2012, accepted 6 August 2012)