

Development of a photoreactive fabric filter for simultaneous removal of VOCs and fine particles

Ok Hyun Park^{*,†}, Chang Soo Kim^{**} and Hyun Hok Cho^{***}

^{*}Department of Environmental Engineering, ^{***}Department of Textile Engineering,
Pusan National University, Busan 609-735, Korea

^{**}Sempio Foods Safety Center (R&D) Researcher, Kyungkido 467-820, Korea
(Received 1 June 2005 • accepted 17 October 2005)

Abstract—A fabric filter sampling system was manufactured by using a UV lamp and a plate-shape sample fabric coated with titanium dioxide (TiO₂) sol to develop a photoreacting fabric filter capable of simultaneously removing dust particles and volatile organic chemicals (VOCs) from contaminated air streams. Variations of pressure drop across the fabric as well as toluene vapor removal efficiency were investigated and examined with respect to various conditions such as the injection duration of dust-laden gas, the photocatalyst particle size, the toluene vapor load, and the photocatalyst load. Again, variations in air permeation and the tensile strength of fabrics with the photocatalyst load were measured and examined to determine the appropriation of nonwoven fabric as a supporter for the photocatalyst. The toluene removal efficiency of this new generation fabric filter was manifestly significant, and a possible deficiency in removal efficiency would be solved through the appropriate design and serial arrangement of a multichannel photoreactor consisting of fabric media coated with the photocatalyst.

Key words: Fabric Filter Sampling System, Titanium Dioxide, Volatile Organic Chemicals, Vapor, Photocatalyst Multichannel Photoreactor

INTRODUCTION

Previous technologies associated with industrial gas cleaning have required separate equipment for the respective treatment of dusts and gaseous pollutants such as volatile organic chemicals (VOCs), with such systems eventually increasing the cost of industrial products. In Japan, a technology to simultaneously remove dusts and gases has been studied recently using a catalyst bag filter, and work on the advanced oxidation process (AOP) has been conducted to treat VOCs and odors in Korea.

Especially, photocatalyst oxidation belonging to AOP is a heterogeneous reaction producing an OH radical that decomposes organic pollutants to form nonhazardous final products such as carbon dioxide and water. The OH radical reacting with most organic materials has an oxidation potential superior to that of other existing oxidants, and its reaction rate is very fast [Glaze et al., 1989; Lee et al., 1998]. Photocatalytic oxidation is considered to be one of the most effective ways to decompose various chlorinated alkenes and other VOCs of low concentrations in gaseous streams, and as a supporter for the photocatalyst, nonwoven fabric is capable to attain sufficient active sites, homogeneity, and the titanium dioxide catalyst adhesion to the surface [Ku et al., 2001]. The filtering materials of non-woven fabric type have wider surface area than those of film or pack type. Thus, the coating treatment of non-woven fabric with TiO₂ maximizes the functional effectiveness of filtration and photooxidation.

In this study, a new filtering material with dual functions as a dust filter and a photocatalyst supporter was provided by coating non-

woven fabric (which is commonly used in industries and is relatively cheap) with the TiO₂ photocatalyst at an optimum load per unit surface area. The fundamental properties of polyester-felted fabrics coated with TiO₂ of various particle sizes were investigated. The application of the newly developed fabric material to a bag filter was also examined. Provided that such a UV/TiO₂ process is confirmed to be capable of removing dusts and gases, the capital and operating costs of treatment facilities cleaning dusty gas streams would be significantly reduced. This study would also contribute to the stimulation of environmental fabric development, and its results could be applied to air cleaners and air conditioners.

EXPERIMENTAL APPARATUS AND METHOD

1. Construction of a Sampling System for a Photoreacting Fabric Filter

A sampling system simulating a photoreacting fabric filter was constructed, as shown in Fig. 1, in order to investigate its dust- and VOC-removal performance. The system was composed of a compressed air storage tank, a diaphragm valve, blow tubes, a blower, a dust feeder, a differential pressure gauge, a UV-C lamp, and a sample fabric coated with the photocatalyst. Moisture was injected into dusty gas at the inlet of the fabric filter sampling system (FFSS) to mitigate pressure drop across the fabric and to improve the efficiency of dust and VOC removal, and a water vapor generator was installed on the downstream side of the blower.

To maintain the relative humidity of flue gas at a constant level, an automatic humidity controller consisting of a WV2200-8 solenoid valve and a moisture sensor was set up in a pipe connected to the vapor generator, and another moisture sensor was placed in the primary mixing chamber located at the downstream side of the blow-

[†]To whom correspondence should be addressed.
E-mail: ohpark@pusan.ac.kr

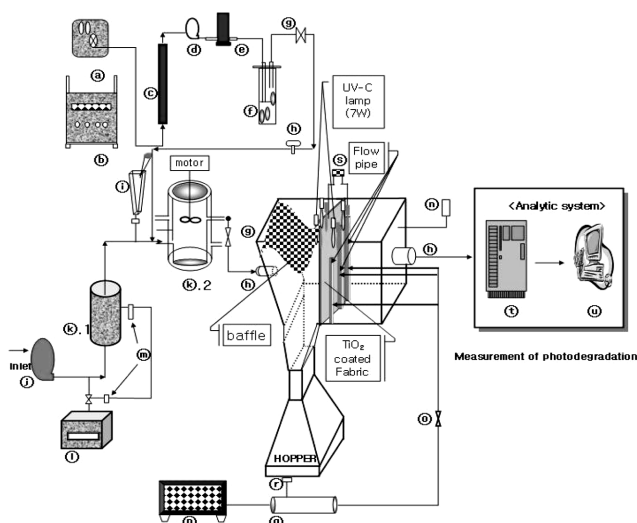


Fig. 1. A fabric filter sampling system equipped with a sample fabric coated with TiO_2 for simultaneous removal of VOC vapors and fine particles.

- | | |
|------------------------|---------------------------------|
| a Air compressor | k 2. Mixing chamber |
| b MFC read out box | l Steam generator |
| c Silicagel | m Automatic humidity controller |
| d Regulator | n Flow meter |
| e Mass flow controller | o Diaphragm valve |
| f Toluene gas | p Air compressor |
| g Check valve | q Air reservoir tank |
| h Sampling port | r Air pressure sensor |
| i Dust feeder | s Differential-pressure gauge |
| j Blower | t GC/FID |
| k 1. Mixing chamber | u Analyzer |

er. A secondary mixing chamber equipped with a stirrer was constructed to facilitate the mixing of water vapor with dust-laden gas and installed at the downstream side of the primary mixing chamber. A screw-type dust feeder was employed, and the dust feeding rate was controlled by using a DC Servo motor. The FFSS was manufactured on a lab scale so that a sample fabric of limited area could be used, and acrylic acid resin (a house construction material) was used so that the dusty gas stream within the FFSS could be visually observed.

To maintain the uniformity of dust approaching the fabric sample, a curved baffle inducing a straight gas stream was placed in front of the sample fabric (size: 30 cm \times 35 cm) coated with TiO_2 sol. UV-C lamps were set up immediately in front and behind the fabric so that the photocatalytic oxidation of VOCs could take place over the surface of the photocatalyst-coated fabric.

Dust lumps detached from the fabric sample by the operation of pulse-jets were allowed to drop down into a hopper. A check valve was set up between the secondary mixing chamber and the inlet of the fabric filter to prohibit possible reverse flows of compressed air and detached dust during cleaning cycles. A flowmeter was installed

at the outlet of the FFSS to continuously measure the flow rate, and pressure sensing probes were placed at the inlet and the outlet of the system so that pressure loss throughout the apparatus could be determined.

2. Materials of Photocatalysts and Fabrics

The raw material of a photocatalyst which has been most widely studied in VOC treatment to this point is TiO_2 powder (Degussa, Germany) with an anatase structure. The powder is used in the sol state. In order to activate the photocatalytic reaction and to observe the effect of UV intensity on the photodegradation efficiency of toluene vapor, 4 blacklight blue lamps (Philips, Holland) with 350–390 nm wavelength and a germicidal lamp (Sankyo Denki, Japan) with 250–265 nm wavelength were separately (not instantaneously) used as the UV sources. The former requires low power and releases radiation with a relatively long wavelength ranging from 350 to 390 nm, and the latter requires high power and releases extreme ultraviolet radiation of 250–265 nm wavelength. The resultant wavelengths of maximum output radiation from the light sources were measured with a UV radiometer (Minolta, Japan), and the wavelengths were revealed to be 379 nm and 250 nm, respectively. The polyester nonwoven fabric used in this study as the photocatalyst supporter was a polyester fabric which has been commonly utilized in industries. Table 1 shows the characteristics of the fabric.

3. Sample Dust and Its Distribution

The dust particulate used in this experiment was fly ash collected from the electrostatic precipitator of a power plant at Hadong, and its true density is 2.65 g/cm³. Drying at 110 °C was performed for 3 hours before usage to maintain uniform levels of moisture. A distribution analysis performed by using a size analyzer (Mastersizer, US) revealed that the mass median, $D(v, 0.5)$, was 14.9 μm , and that the cumulative 90 and 10 percentile diameters were 60.1 μm and 0.73 μm , respectively. The major components of the fly ash, distinguished by XRF (X-ray Fluorescence Spectrometry), were SiO_2 (56.36% by wt), Al_2O_3 (31.54%), CaO (3.75%), and Fe_2O_3 (3.40%).

4. Analytical Methods

Gas chromatography (Perkins-Elmer Autosystem XL) with FID was used to determine the concentration of toluene vapors. Concerning the operating conditions for the GC-Autosystem XL, the temperature of the column, detector, and sample injecting port were 120, 220, and 200 °C, respectively, and the flow rates for carrier gas (N_2), combustion gas (H_2), and supplementary air were 50, 50, and 550 ml/min, respectively.

RESULTS AND DISCUSSION

1. Variations of Dust and Toluene-Vapor Removal Efficiency with Duration of Filtration-Cleaning Cycle

Since the gas flow rate should be restricted in a fabric filter under consideration of pressure loss and dust removal efficiency, dust/toluene removal experiments were carried out within the limited

Table 1. Characteristics of the polyester non-woven fabric

| Weight (g/mm ³) | Thickness (mm) | Air permeability (cc/cm ³ /sec) | Tensile strength (kg/25 mm) | Thermal resistance | Chemical resistance |
|--------------------------------|-------------------|---|--------------------------------|-----------------------|------------------------|
| 500 | 1.8 | 16 | >170 | ~130 °C | strong against acid |

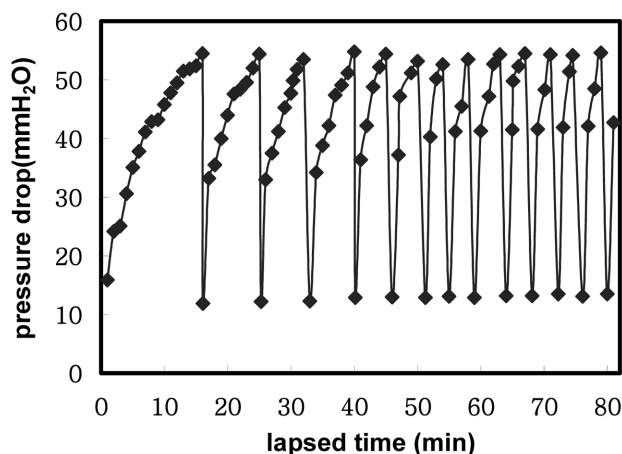


Fig. 2. Variation of pressure drop with time during filtration-cleaning cycles in a TiO_2 -coated fabric filter ($d_n=10$ mm, $P_{do}=2$ kg/cm², $C_p=39.06$ g/min, $V=1.4$ m/min, R.H.=40%, catalyst loading=11.2 mg (TiO_2)/cm² (fabric), UV intensity=7 W/cm²).

superficial filtration velocity range of 0.5 to 1.4 m/min using an FFSS. Although the porosity of the non-woven fabric is about 70%, TiO_2 sol cannot infiltrate through the openings, but forms a cake layer on the fabric surface. The photocatalyst load per unit fabric area appeared not to vary with cleaning cycles using reverse air flow due to the use of an inorganic binder during TiO_2 sol production.

Fig. 2 reveals variations in pressure drop (ΔP) across a TiO_2 -coated polyester fabric with time during filtration-cleaning cycles, and it shows that the filtration duration decreases and that the reverse jet frequency per unit time interval increases with operating time for a given ΔP value. These facts suggest that the residual pressure loss immediately after reverse-jet cleaning increases as the operation continues. These also suggest that the maintenance cost due to the wear of fabrics increases in a photoreacting fabric filter. Thus, it is

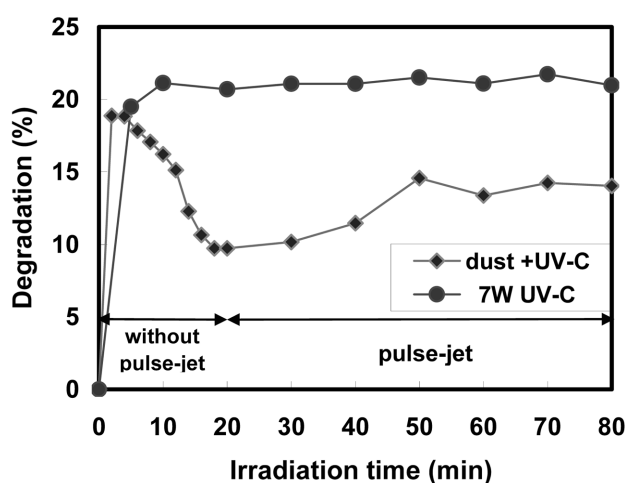


Fig. 3. Variation of the photocatalytic degradation of toluene vapor with time during filtration-cleaning cycles in a TiO_2 -coated fabric filter ($d_n=10$ mm, $P_{do}=2$ kg/cm², $C_p=39.06$ g/min, $V=3.8$ m/sec, R.H.=50%, UV intensity=7 W/m², $C_o=7$ ppm, catalyst loading=11.02 mg (TiO_2)/cm² (fabric)).

necessary to appropriately establish the reverse air pressure, the photocatalyst-layer thickness, and the upper limit of the pressure drop in order to maintain a good cleaning effect.

Fig. 3 shows that when dust-laden air polluted with toluene vapor is introduced into a photoreacting fabric filter, the toluene removal efficiency rapidly decreases with dust-cake build-up above the photocatalyst film because catalytic activity was lowered due to the accumulation of carbonaceous materials on the surface of catalyst particles as found by Yoo et al. [2003]; however, the efficiency can eventually be maintained at 60-70% of the initial level as the cleaning cycle using pulse-jets repeats every 5 min. In this figure, the control data were taken for the conditions with only UV and toluene vapor. Those for with dust without UV were not obtained because the toluene vapor concentration should not be significantly decreased by adsorption to porous particles in such control case due to the lab-scale apparatus resulting very short residence time. A possible deficiency in VOC-removal efficiency could be removed by using additional equipment such as a serial monolith photoreactor or a multi-channel photoreactor with TiO_2 -coated fabrics for ease of operation [Na et al., 2003; Park and Kim, 2004].

2. Variation of Photocatalytic Activity with Duration of Photocatalyst Usage

Although gas purification using a photocatalyst is notable compared with such methods as combustion and biofiltration due to merits such as efficiency, cost economy and safety, there are problems such as deactivation, which should be solved in order to develop the technology to a commercially-viable stage. As a regeneration method of deactivated photocatalyst, Dipple and Raupp [1992] suggested the injection of low-humidity air which contributes to the decomposition of accumulated carbon species by water and to the hampering of the deposition of intermediates on the photocatalyst surface [Dipple et al., 1992]. Cao et al. [2000] confirmed that a deactivated TiO_2 catalyst can be completely regenerated by burning out the chem-

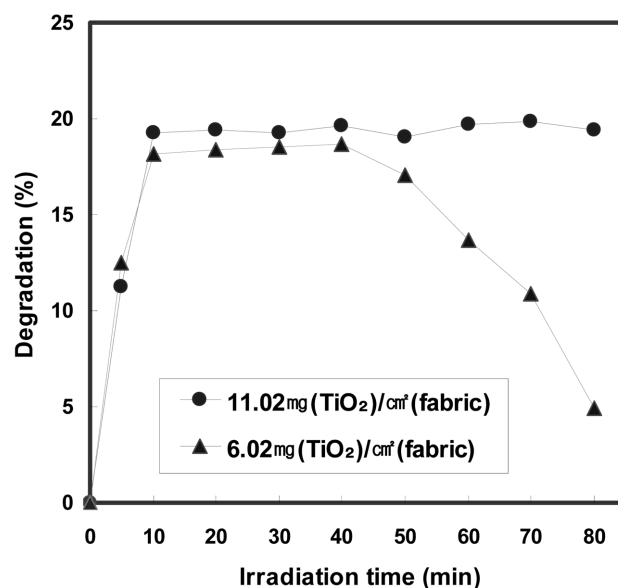


Fig. 4. Photocatalytic degradation of toluene vapor in a bag filter equipped with polyester fabric coated with different catalyst loadings ($C_o=7$ ppm, $T=20$ °C, UV intensity=7 W/m², $V=3.8$ m/sec, R.H.=50%).

isorbed carbon species above 420 °C [Cao et al., 2000]. They found that the recoupling frequency of electron-hole pairs increases under excessive moisture condition, which is another cause of photocatalyst deactivation.

In this study, experiments on the conversion of toluene vapor under conditions of constant humidity but different catalyst loads were conducted using an FFSS equipped with a TiO₂-coated fabric sample (Fig. 1) to investigate the deactivation phenomenon of the photocatalyst. The results are expressed in Fig. 4, where the rapid reduction of photocatalyst activity after 40 min of UV irradiation under the catalyst load condition of 6.02 mg (TiO₂)/cm² (fabric) is shown. This appears to indicate that there is a limitation in VOC conversion rate by unit TiO₂ mass.

3. Variation of Coated-Fabric Characteristics and Toluene Conversion Rate with TiO₂-Particle Size

Since the photocatalytic reaction leading to gas purification takes place on the catalyst's surface, the surface area of catalyst particles has a direct relation to the initial reaction rate [Cao et al., 2000]; however, it has been known that the photoreaction rate is not proportional to the catalyst's mass [Anpo et al., 1987]. According to Anpo et al. [1987], the photocatalytic activity increases as the size of the photocatalyst particles becomes smaller, especially in a range smaller than 100 Å in diameter. The different dependence of the photocatalytic yields on the particle diameter of the TiO₂ catalyst suggests that the differences in photocatalytic activity arise from differences in the reactivity, but not in the physical properties such as the surface area of these catalysts. Reductions of size might result in some electronic modification of TiO₂ to produce an enhancement of the activities of electrons and holes, and/or a suppression of the radiationless transfer of absorbed photon energies. The surface area of TiO₂ particles is 72.15 m²/g for the 50 nm size and 119.8 m²/g for the 5 nm size, respectively. Figs. 5 and 6 comparatively express the tensile strength and air permeability of fabric supporters after dip-coating with solutions of TiO₂, the particle sizes of which are 5 nm and 50 nm, respectively. The values are averages of five measurements, respectively, obtained according to the Frazier method (KS K0570-1997) for air permeability and the strip method (KS

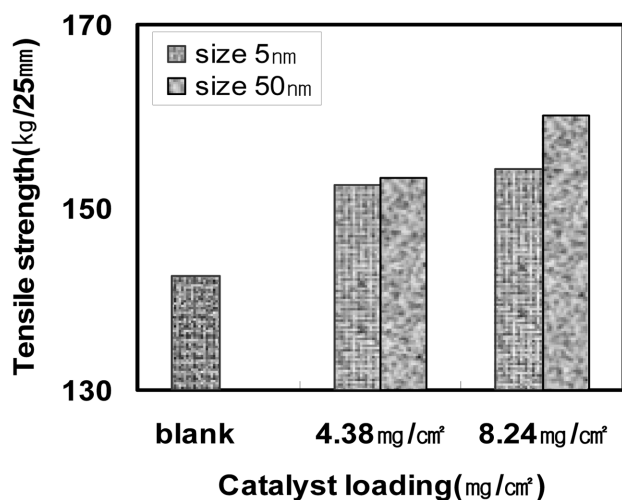


Fig. 5. Fabric tensile strength versus catalyst loading for different TiO₂ particle sizes.

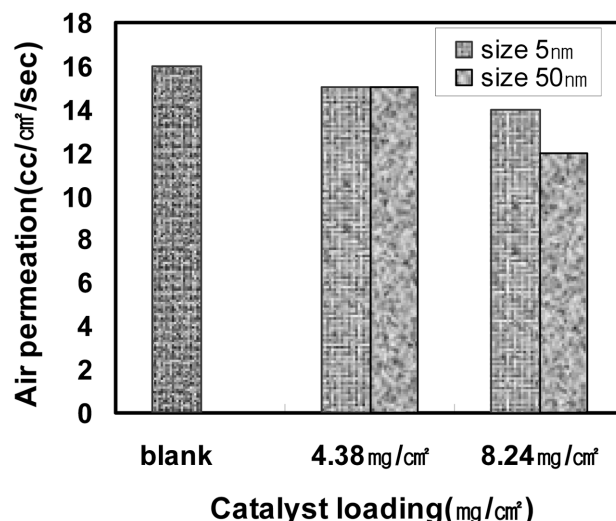


Fig. 6. Air permeation versus catalyst loading for different TiO₂ particle sizes.

K0521-2001) for tensile strength. As shown in Fig. 5, the tensile strength of fabrics coated with TiO₂ particle solution increased by about 7-11% compared with uncoated fabrics. This improvement in tensile strength would enhance the quality of fabric to be used in a bag filter where dust cake is cleaned in pulse-jet fashion. Fig. 6 reveals that fabrics coated with TiO₂ particle of 5 nm maintain better air permeability than those with TiO₂ of 50 nm, but the permeability decreases as the photocatalyst load per unit fabric area increases. Fig. 7 shows that when polyester non-woven fabrics coated with TiO₂ powder of 5 nm were used in an FFSS equipped with UV light sources, the efficiency of toluene-vapor removal from air stream improved to about 5 times that for TiO₂ of 50 nm under constant conditions of toluene vapor concentration, UV light intensity, flow rate, photocatalyst load, humidity, and gas load per unit fabric area. This appears to be due to the larger surface area, exposed to UV light, of whole photocatalyst particles of 5 nm diameter rather than

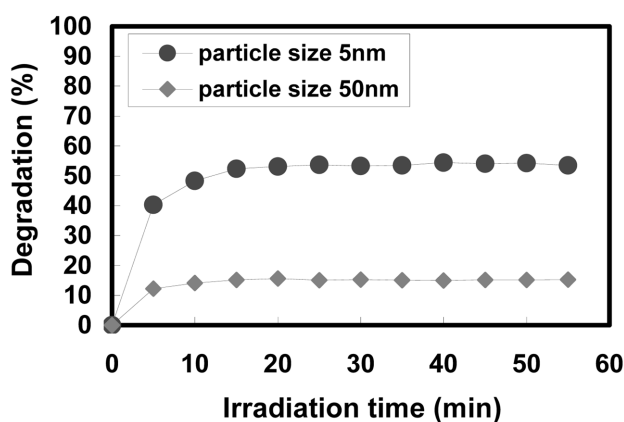


Fig. 7. Toluene vapor degradation versus irradiation time for different TiO₂ particle sizes ($C_0=7$ ppm, UV intensity=7 W/m², temperature=25 °C, flowrate=1 L/min, catalyst loading=2 mg (TiO₂)/cm² (fabric) R.H.=38.5%, number of channels=2).

that for 50 nm size under constant conditions of photocatalyst load per unit fabric area. The higher photocatalytic activities appear to originate from the greater amount of photogenerated electron-hole pairs, which were transferred from the inside to the surface of TiO_2 films [Xianyu et al., 2001].

CONCLUSIONS

This study was conducted to develop an integrated technology for removing dusts and VOCs simultaneously from contaminated air streams by employing a photoreacting filter with TiO_2 -coated fabrics. Pressure drop across a sample fabric and toluene vapor removal efficiency were measured by using a fabric filter sampling system on a lab scale under varying conditions of toluene vapor concentration, photocatalyst particle size, photocatalyst load per unit fabric area, and the injection duration of dust-laden gas. Variations in tensile strength and the air permeability of fabrics with the photocatalyst load were also measured to determine the appropriateness of non-woven fabric as a support for a photocatalyst. The following conclusions were drawn based on the examination of the experimental results.

As the operation of a photoreacting filter with photocatalyst-coated fabric proceeds under a set pressure-drop condition, the duration of dust filtration gradually shortens and the frequency of dust cleaning in pulse-jet cleaning fashion increases. This suggests that appropriate determinations of reverse-air pressure, blow-pipe nozzle size, photocatalyst film thickness, and a set pressure-drop point are necessary to maintain the proper cleaning effect.

It was confirmed that the toluene-vapor removal efficiency before pulse-jet operation for dust cake detachment decreases rapidly as dust cake builds up, and that it then regains 60-70% of its initial level after the starting of the pulse-jets operation in a filter sampling system equipped with photocatalyst-coated fabric and UV light sources. Insufficiency in gas removal efficiency can be effectively compensated for by employing a multichannel photoreactor using non-woven fabric as a support for the photocatalyst.

The catalytic activity of TiO_2 rapidly decreased with operation time in a photoreactor with TiO_2 -coated fabric under constant humidity conditions, providing that the TiO_2 load per unit fabric area was less than the appropriate value. This suggests that there is a limitation in VOC-conversion capacity per unit mass of pure TiO_2 .

The tensile strength of non-woven fabric increased by about 10% through dip-coating in TiO_2 powder solution. This improvement is favorable for a photoreacting fabric filter employing pulse-jets for dust cleaning. The air permeability of fabric coated with TiO_2 powder of smaller particle size is better than that of fabric coated with particles of larger sizes ranging below 50 nm, provided that the photocatalyst load per unit fabric area is equal; however, the air permeability decreases with the photocatalyst load.

The efficiency of the removal of toluene vapor from air in a photoreacting filter equipped with fabrics coated with 5 nm of TiO_2 par-

ticles improved by up to about 3 times that for the 50 nm size under constant operating conditions of UV light intensity, gas load per unit fabric area, photocatalyst load per unit fabric area, and relative humidity.

NOMENCLATURE

| | |
|-----------|---|
| C_0 | : initial vapor concentration [ppm] |
| C_p | : dust loading [g/min] |
| d_n | : nozzle diameter [mm] |
| P_{tko} | : initial tank pressure [kg/cm ²] |
| R.H. | : flue gas relative humidity [%] |
| T | : temperature [°C] |
| V | : filtration velocity [m/min] |

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