

# **DEVELOPMENT OF A PHOTOREACTING FABRIC FILTER FOR SIMULTANEOUS REMOVAL OF VOC VAPORS AND FINE PARTICLES**

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## **ABSTRACT**

A fabric filter sampling system was manufactured using a UV lamp and a plate-shape sample fabric coated with titanium dioxide ( $\text{TiO}_2$ ) sol to develop a photoreacting fabric filter capable of simultaneously removing dust particles and volatile organic compounds (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 appropriateness 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 consisted of fabric media coated with the photocatalyst.

## **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 compounds (VOCs), and such systems eventually increase the cost of industrial products. In Japan, technology to simultaneously remove dusts and gases has been studied recently using a catalyst bag filter, and a number of works on advanced oxidation process (AOP) have 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 [4],[6]. 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 [5].

In this study, a new filtering material with dual functions as a dust filter and a photocatalyst supporter was provided by coating nonwoven fabric (which is commonly used in industries and is relatively cheap) with the  $\text{TiO}_2$  photocatalyst at an optimum load per unit surface area. The application of the newly developed fabric material to a bag filter was also examined. Provided that such a UV/ $\text{TiO}_2$  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**

### **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 blower. 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 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 a 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 × 35 cm) coated with TiO<sub>2</sub> 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.

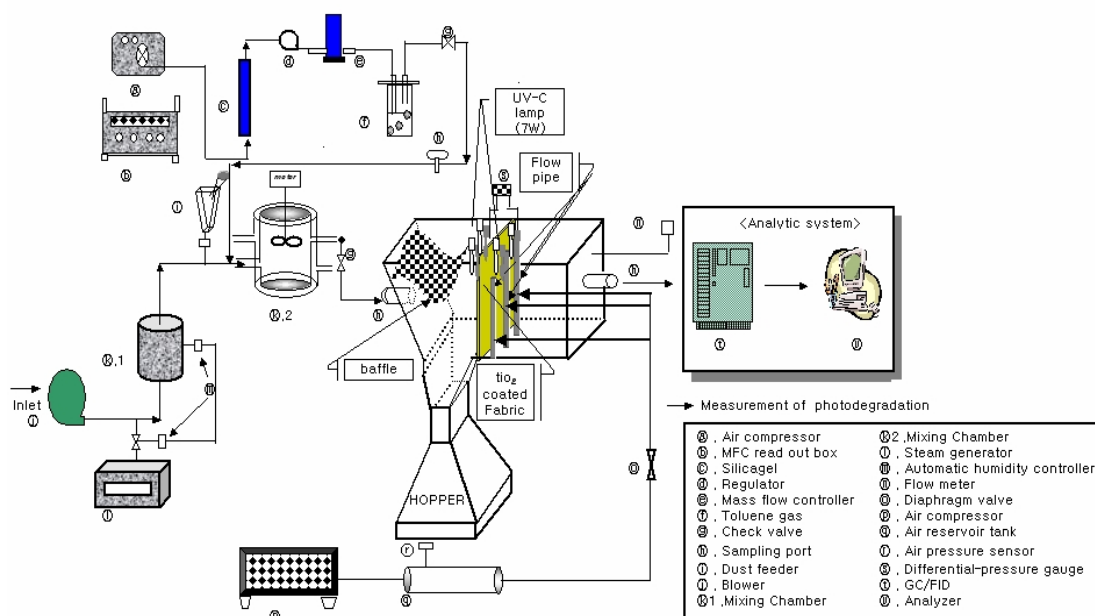


Fig. 1. A filter sampling system equipped with a sample fabric coated with TiO<sub>2</sub> for simultaneous removal of VOC vapors and fine particles

### 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<sub>2</sub> powder (Degussa, Germany) with an anatase structure. The powder is used in the sol state. In order to activate the photocatalytic reaction, 4 blacklight blue lamps (Philips, Holland) and a germicidal lamp (Sankyo Denki, Japan) were 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 using a UV radiometer (Minolta, Japan), and the wavelengths were revealed to be 379 nm and 250 nm, respectively. The sample nonwoven fabric used in this study as the photocatalyst supporter was a polyester fabric which has been commonly utilized in industries.

### **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/cm<sup>3</sup>. 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 analyser (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<sub>2</sub> (56.36% by wt), Al<sub>2</sub>O<sub>3</sub> (31.54%), CaO (3.75%), and Fe<sub>2</sub>O<sub>3</sub> (3.40%).

## **EXPERIMENTAL RESULTS AND DISCUSSION**

### **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 superficial filtration velocity range of 0.5 to 1.4 m/min using an FFSS. Although the porosity of nonwoven fabric made with glass fiber and polyamid or poly-4fluorethylene fiber is about 70%, TiO<sub>2</sub> 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<sub>2</sub> sol production.

Figure 2 reveals variations in pressure drop ( $\Delta P$ ) across a TiO<sub>2</sub>-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  $\Delta P$  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 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.

Figure 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; 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. A possible deficiency in VOC-removal efficiency could be removed by using additional equipment such as a multichannel photoreactor [7] with TiO<sub>2</sub>-coated fabrics for ease of operation.

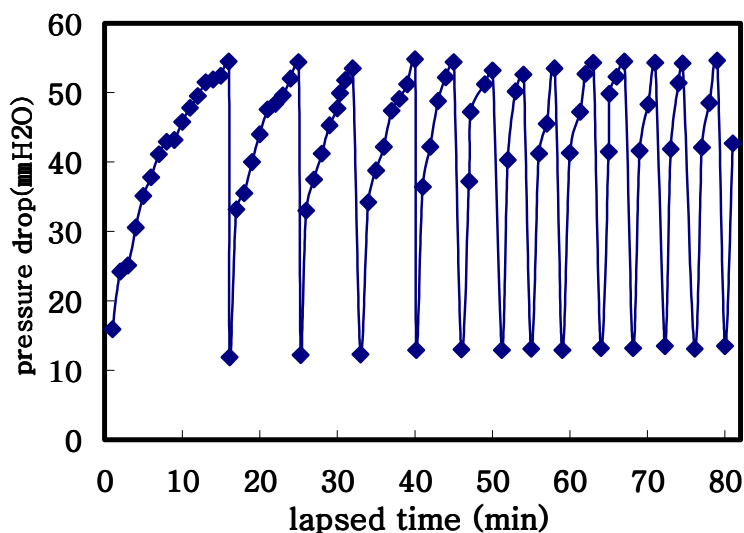


Fig. 2. Variation of pressure drop with time during filtration-cleaning cycles in a TiO<sub>2</sub>-coated fabric filter ( $d_n = 10$  mm,  $P_{tko} = 2$  kg/cm<sup>2</sup>,  $C_p = 39.06$  g/min,  $V = 1.4$  m/min, R.H. = 40%, catalyst loading = 11.2 mg (TiO<sub>2</sub>)/cm<sup>2</sup> (fabric), UV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

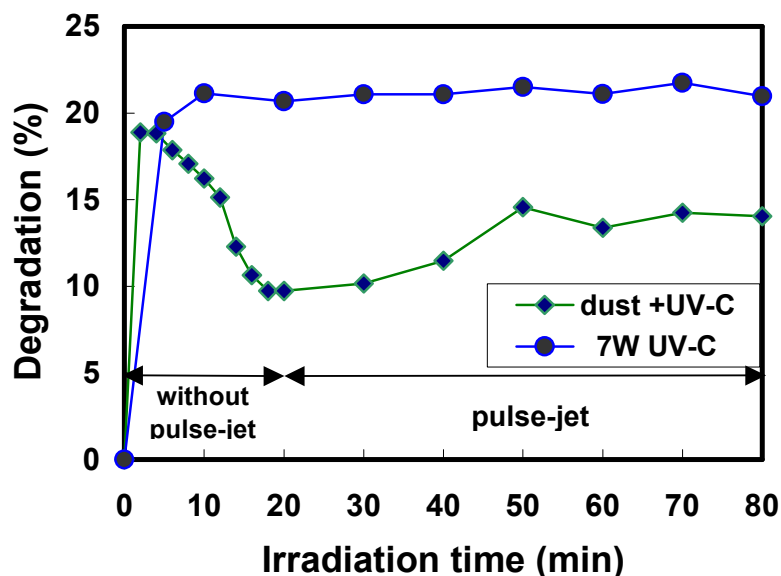


Fig. 3. Variation of the photocatalytic degradation of toluene vapor with time during filtration-cleaning cycles in a  $\text{TiO}_2$ -coated fabric filter ( $d_n = 10 \text{ mm}$ ,  $P_{tko} = 2 \text{ kg/cm}^2$ ,  $C_p = 39.06 \text{ g/min}$ ,  $V = 3.8 \text{ m/sec}$ , R.H. = 50%, UV intensity =  $7 \text{ W/cm}^2$ ,  $C_o = 7 \text{ ppm}$ , catalyst loading =  $11.02 \text{ mg (TiO}_2\text{)/cm}^2 \text{ (fabric)}$ )

### 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 [2]. Cao et al. (2000) confirmed that a deactivated  $\text{TiO}_2$  catalyst can be completely regenerated by burning out the chemisorbed carbon species above  $420^\circ\text{C}$ . 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 TiO<sub>2</sub>-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 (TiO<sub>2</sub>)/cm<sup>2</sup> (fabric) is shown. This appears to indicate that there is limitation in VOC conversion rate by unit TiO<sub>2</sub> mass.

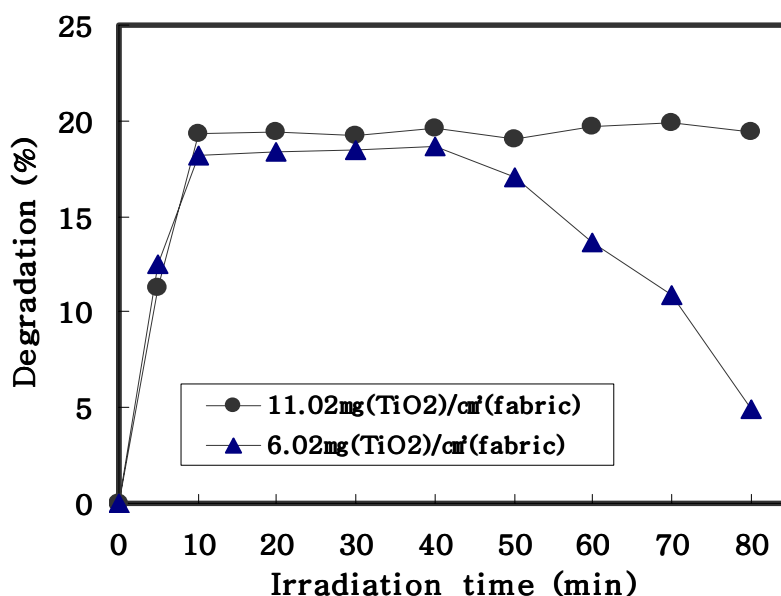


Fig. 4. Photocatalytic degradation of toluene vapor in a bag filter equipped with polyester fabric coated with different catalyst loadings (Co = 7 ppm, Temperature = 20°C, UV intensity = 7 W/m<sup>2</sup>, V = 3.8 m/sec, R.H. = 50%)

#### Variation of coated-fabric characteristics and toluene conversion rate with TiO<sub>2</sub>-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 [2]; however, it has been known that the photoreaction rate is not proportional to the catalyst's mass [1]. According to Anpo et al. (1987), the photocatalytic activity increases as the size of the photocatalyst particles become smaller, especially in the range smaller than 100 nm in diameter. The different dependence of the photocatalytic yields on the particle diameter of the

TiO<sub>2</sub> 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 TiO<sub>2</sub> 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 TiO<sub>2</sub> particles is 72.15 m<sup>2</sup>/g for the 50 nm size and 119.8 m<sup>2</sup>/g for the 5 nm size, respectively. Fig. 5 and Fig. 6 comparatively express the tensile strength and air permeability of fabric supporters after dip-coating with solutions of TiO<sub>2</sub>, the particle sizes of which are 5 nm and 50 nm, respectively. The values are averages of 5 measurements, respectively, obtained according to the Frazier method (KS K0570-1997) for air permeability and the strip method (KS K0521-2001) for tensile strength. As shown in Fig. 5, the tensile strength of fabrics coated with TiO<sub>2</sub> 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 TiO<sub>2</sub> particle of 5 nm maintain better air permeability than those with TiO<sub>2</sub> of 50 nm, but the permeability decreases as the photocatalyst load per unit fabric area increases. Fig. 7 shows that when polyester-felted fabrics coated with TiO<sub>2</sub> 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 TiO<sub>2</sub> 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.



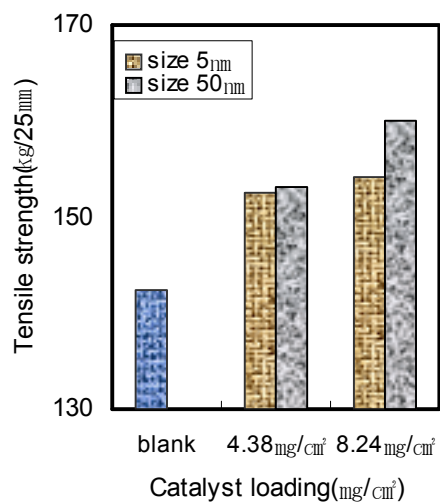


Fig. 5. Fabric tensile strength versus catalyst loading for different TiO<sub>2</sub> particle sizes

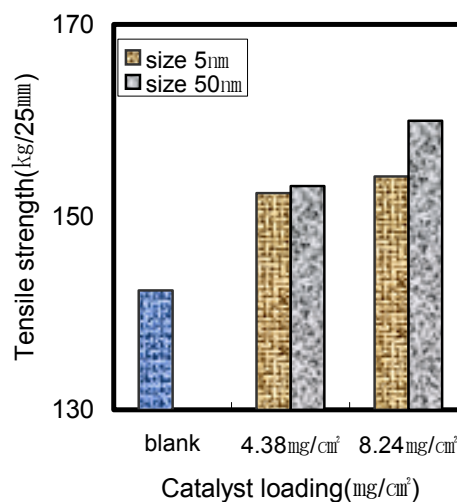


Fig. 6. Air permeation versus catalyst loading for different TiO<sub>2</sub> particle sizes

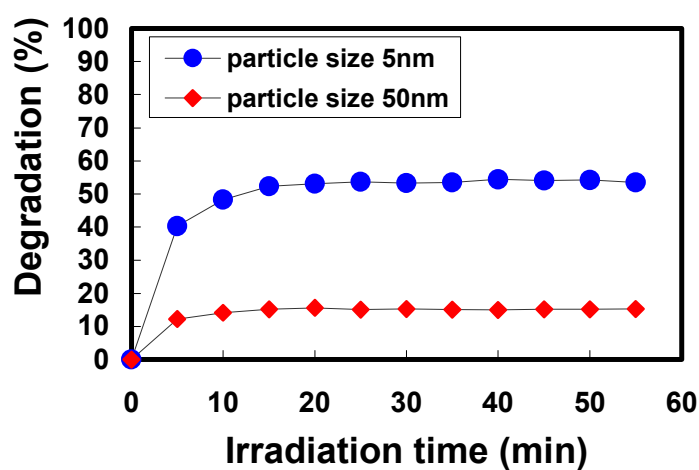


Fig. 7. Toluene vapor degradation versus irradiation time for different TiO<sub>2</sub> particle sizes

## 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<sub>2</sub>-coated fabrics. Pressure drop across a sample fabric and toluene vapor removal efficiency were measured 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 nonwoven fabric as a supporter for a photocatalyst. The following conclusions were drawn based on the examination of the experimental results.

1. As the operation of a photoreacting filter with photocatalyst-coated fabric proceeds under a given pressure-drop condition, the duration of dust filtration gradually shortens and the frequency of dust cleaning in pulse-jet 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.

2. 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 in a filter sampling system equipped with photocatalyst-coated fabric and UV light sources. Insufficiency in gas removal efficiency can be effectively compensated by employing a multichannel photoreactor using felted fabric as a supporter for the photocatalyst.

3. The catalytic activity of TiO<sub>2</sub> rapidly decreased with operation time in a photoreactor with TiO<sub>2</sub>-coated fabric under constant humidity conditions, providing that the TiO<sub>2</sub> 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<sub>2</sub>.

4. The tensile strength of felted fabric increased by about 10% through dip-coating in TiO<sub>2</sub> powder solution. This improvement is favourable for a photoreacting fabric filter employing pulse-jets for dust cleaning. The air permeability of fabric coated with TiO<sub>2</sub> 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.

5. The efficiency of the removal of toluene vapor from air in a photoreacting filter equipped with fabrics coated with 5 nm of TiO<sub>2</sub> particles 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.

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