Effectiveness of Photocatalytic Filter for Removing Volatile Organic Compounds in the Heating, Ventilation, and Air Conditioning System

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ABSTRACT

Nowadays, the heating, ventilation, and air conditioning (HVAC) system has been an important facility for maintaining indoor air quality. However, the primary function of typical HVAC systems is to control the temperature and humidity of the supply air. Most indoor air pollutants, such as volatile organic compounds (VOCs), cannot be removed by typical HVAC systems. Thus, some air handling units for removing VOCs should be added in typical HVAC systems. Among all of the air cleaning techniques used to remove indoor VOCs, photocatalytic oxidation is an attractive alternative technique for indoor air purification and deodorization. The objective of this research is to investigate the VOC removal efficiency of the photocatalytic filter in a HVAC system. Toluene and formaldehyde were chosen as the target pollutants. The experiments were conducted in a stainless steel chamber equipped with a simplified HVAC system. A mechanical filter coated with Degussa P25 titania photocatalyst and two commercial photocatalytic filters were used as the photocatalytic filters in this simplified HVAC system. The total air change rates were controlled at 0.5, 0.75, 1, 1.25, and 1.5 hr⁻¹, and the relative humidity (RH) was controlled at 30%, 50%, and 70%. The ultraviolet lamp used was a 4-W, ultraviolet-C (central wavelength at 254 nm) strip light bulb. The first-order decay constant of toluene and formaldehyde found in this study ranged from 0.381 to 1.01 hr⁻¹ under different total air change rates, from 0.34 to 0.433 hr⁻¹ under different RH, and from 0.381 to 0.433 hr⁻¹ for different photocatalytic filters.

IMPLICATIONS

Photocatalytic oxidation is a greatly attractive alternative technique for indoor air cleaning. This study introduces photocatalytic oxidation air handling units into the HVAC system to remove the VOCs contaminations. The data, such as the VOC removal efficiency of photocatalytic filter and the clean air delivery rate, provided by this research are useful in real-system application.

INTRODUCTION

The heating, ventilation, and air conditioning (HVAC) system is a common facility nowadays for maintaining indoor air quality. Air handling units in typical HVAC systems generally contain: (1) outside air intakes, plenums, ducts, and outdoor air; (2) filters and prefilters; (3) heating and cooling coils; (4) chiller and boiler (to supply hot and chilled water for the coils); (5) cooling towers; (6) humidifier or dehumidifier; (7) supply fans; (8) supply ducts; (9) distribution ducts, boxes, and plenums; (10) damper; (11) return air plenums or ducts; (12) return fan; and (13) exhaust outlets. The primary function of typical HVAC systems is to control the temperature (thermal comfort) and relative humidity (RH) of the supply air. The components in a HVAC system that are capable of removing the air pollutants contain the filter and prefilter. The mechanical (or electrostatic) filter is used for the control of the particulates. Some HVAC systems may be equipped with sorbent filters, such as active carbon filter, to remove gaseous contaminants or vapor emitted from the building elements. However, many studies demonstrated that the used filters, which are used to remove particles from the passing air, may pollute the air instead of cleaning it.^{1,2} The filter itself and the captured particulates may act as amplification sites for biological contaminants under high RH,^{3,4} and the biological contaminant is one of the important sources of indoor volatile organic compounds (VOCs). The problem with using sorbent filters is the breakthrough of sorbent. When temperature or humidity increases, the adsorbed VOCs may be desorbed and then may re-enter the airstream. After exhausted, the sorbent filters need further treatment, such as regeneration or disposal of the spent sorbent.

Photocatalytic oxidation (PCO) of gas-phase VOCs appears to be a promising alternative process for removing VOCs in HVAC systems. This process is effective in controlling a wide variety of VOCs, including alkanes, alkenes, alcohol, aromatics, chlorinated hydrocarbons, aldehydes, and ketones.^{5–9} Rather than adsorbing VOCs on sorbent, the photocatalytic filter can oxidize VOCs to carbon dioxide (CO₂) and water (H₂O). Furthermore, many studies showed that the PCO process is able to

Figure 1. Diagram of the test chamber and the HVAC system.

control the biological contaminations.^{10–12} In this study, we used a small chamber system to investigate the VOC removal efficiency of the photocatalytic filter in the HVAC system. This chamber system includes a stainless steel chamber and a simplified HVAC system. Three types of photocatalytic filters were used in the experiments. The experiments were conducted under different total air change rates and RH to investigate the effects of these two environmental factors on the VOC removal efficiency. Toluene and formaldehyde were chosen as the target VOCs pollutants. Both toluene and formaldehyde are frequently encountered organic compounds in indoor environments. Toluene can cause irritation to eyes, nose, mucous membrane, and respiratory tract.^{13–15} Exposure to formaldehyde of concentration ≥ 0.25 mg/m³ can cause irritation to eyes, nose, and throat.¹⁶ Inhaling formaldehyde fumes can result in respiratory tract irritation and impairment of lung function. Formaldehyde has been proven to be a carcinogen,^{17,18} and it may possess reproductive toxicology. According to many gene mutation assays results, exposure to formaldehyde would lead to DNA-protein cross-links and DNA single-strand breaks.¹⁹ Toluene and formaldehyde were chosen as the surrogates for the six major classes of indoor VOCs (aromatic, aldehyde, alkane, ketone, alcohol, and chlorocarbon) by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers for testing air filtration equipment.²⁰

EXPERIMENTAL WORK

Experimental System

The experiments were conducted in an $80 \times 80 \times 80$ cm³ stainless steel chamber equipped with an HVAC system. To eliminate the confounding effects of other components, this HVAC system was simplified and contained only a duct system (cross-section: 6×6 cm²), a supply fan, a return fan, a photocatalytic filter (3.8×3.8 cm²), and an ultraviolet (UV) lamp. Figure 1 shows the diagram of the experimental system.

A mechanical filter coated with Degussa P25 titanium dioxide (TiO₂) photocatalyst (3.6 mg TiO₂/cm²-filter) and two commercial photocatalytic filters were used in the

experiments. Degussa P25 TiO₂ powder has a primary particle diameter of 30 nm, a surface area of 50 m²/g (Brunauer, Emmett, and Teller [BET]), and a crystal structure of 70% anatase and 30% rutile.^{5,6} The TiO₂ coating procedure was described as follows.^{8,21,22} First, the TiO₂ powder was suspended in distilled water by the ultrasonic tank (Branson 5200). Then, the filter was immersed in the TiO₂ sludge. After the filter became dry, a TiO₂ coating remained on the surface of the filter. The UV lamp used in the experiments was a 4-W, UV-C (central wavelength at 254 nm) strip light bulb. This lamp was chosen because the absorbance of TiO₂ is greatest at 254 nm.²³ The configuration of the photocatalytic filter system is shown in Figure 2. The light flux at the filter surface was measured by the UVX radiometer (Model UVX-36, UVP) at nine points. The result of the measurement is shown in Figure 3. The ozone concentration in the chamber was monitored continuously by ozone analyzer model 400A (API Inc.).

Mixing Level of the Test Chamber

To obtain the adequate mixing level (>80%), a fan was installed in the test chamber. The mixing level of the test chamber was calculated as below:

$$\eta\% = \left\{ 1 - \frac{\sum_{i=1}^n [C_{tr}(t_i) - C_{th}(t_i)] \times (t_i - t_{i-1})}{\sum_{i=1}^n [C(t_i) \times (t_i - t_{i-1})]} \right\} \times 100\% \quad (1)$$

where η (%) is the mixing level, t_i (hr) is the time when the i^{th} sample was taken, n is the serial number of the sample, and $C_{tr}(t_i; \text{ppm})$ is the gaseous tracer (CO₂) concentration at time t_i . $C_{th}(t_i; \text{ppm})$ is the theoretical tracer concentration under a completely mixing condition, and $C_{th}(t_i)$ can be calculated by the following equation:

Figure 2. Configuration of the photocatalytic filter and the UV lamp system.

C_{th}(t_i) = C_{tr}(0)e^{-Ach×t} (2)

in which C_{tr} (0) is the initial gaseous tracer concentration (ppm), and Ach is the air change rate of the test chamber (hr⁻¹). Q-Trak (TSI. 8550) was used to monitor the CO₂ concentration continuously. The mixing levels of test 1 and test 2 were 96.4% and 96.6%, respectively, as shown in Table 1.

Sampling and Analysis of VOCs

Toluene and formaldehyde were chosen as the target VOCs of this study. The sampling apparatus for toluene included 500-mg Tenax TA (60/80 mesh) cartridges (SUPELCO) and a personal sampling pump (SKC). The sampling flow rate was 25 mL/min, and the sampling time

was 6 min. The cartridges were purged with nitrogen gas (purity: 99.9%, flow rate: 30 mL/min) under 230 °C for ~2–4 hr before use. After sampling, the Tenax TA cartridges were thermal desorbed and cryofocussed by Aero Trap Desorber (TEK-MAR 6000) and then analyzed by the gas chromatography (GC) and the flame-ionization detector (HP5890 series II). The quantification was conducted as described. First, we injected 1-μL reference solution into a 125-mL glass sampling bulk (SUPELCO). After the reference solution was evaporated, the air in the sampling bulk was flushed out by compressed air at a flow rate of 25 mL/min, and the tail gas was sampled on a Tenax TA cartridge for 10 min and then analyzed by the GC system. Based on the analytic results of a series of reference solutions of toluene, a calibration curve was created. The sampling apparatus for formaldehyde contained LpDNPH S10 air monitoring cartridges (SUPELCO) and a personal sampling pump (SKC). The sampling flow rate was 200 mL/min, and the sampling volume was 2000 mL. After sampling, the LpDNPH S10 cartridge was eluted with 2-mL aliquots of acetonitrile, and the eluate was collected to the 10-mL mark on a volumetric flask. The extract was analyzed with GC-photoionization detection ([GC-PID] HP5890 series II), and the injected volume was 2 μL. The quantification was conducted by analyzing a

	1.25 cm	1.25 cm	1.25 cm
1.25 cm	43±2 μW/cm ²	45±2 μW/cm ²	43±2 μW/cm ²
1.25 cm	59±2 μW/cm ²	60±2 μW/cm ²	59±2 μW/cm ²
1.25 cm	43±2 μW/cm ²	45±2 μW/cm ²	43±2 μW/cm ²

Figure 3. The UV intensity measured at nine points (center of each square) of the filter surface.

Table 1. Mixing level of test chamber.

Test	Initial CO ₂ Concentration (ppm)	Temperature (°C)	RH (%)	ACH (hr ⁻¹)	Mixing Level (%)
1	3392	25.4	66.3	1.0	96.4
2	4438	25.9	67.4	1.0	96.6

ACH indicates air change rate in the test chamber.

series of reference solutions of formaldehyde with the GC system (HP5890 series II GC-PID). A calibration curve was created based on the analytic result of the reference solutions of formaldehyde.

Experiment Setup

Before the experiments started, the stainless steel chamber was conditioned for ~6 hr to attain the required experimental conditions. The experiments were conducted under RH of 30%, 50%, and 70% and total air change rates of 0.5, 0.75, 1, 1.25, and 1.5 hr⁻¹ (recirculation rate is 50%). Then, the UV lamp was turned on and warmed up for 15 min. The VOC solvent was injected into the chamber when the condition procedure was finished. After the VOC was completely evaporated, the experiments got started. The outlet air of the chamber was sampled on Tenax TA cartridges (for toluene) or LpDNPH S10 cartridges (for formaldehyde) for every 30 min and then analyzed by the GC system immediately after sampling. The control experiments were performed in the same way but with the UV lamp off. The experiments were conducted with and without the photocatalytic filter to provide evidence for how much VOC removal was being caused by the photocatalytic filter and how much VOC removal resulted from the direct gas-phase photochemistry.

RESULTS AND DISCUSSION

Natural Decay and Decay Constant

In this study, the mass balance of VOCs within the test chamber can be described as the following differential equation:

$$V \frac{dC}{dt} = QR_r C(1 - \eta_{PF}) - QC \quad (3)$$

where V (m³) is the volume of the test chamber; C (ppm) is the average VOC concentration in the chamber; Q (m³/hr) is the airflow rate passing through the photocatalytic filter; R_r is the recirculation rate (in this study, $R_r = 0.5$); and η_{PF} is the VOC removal efficiency of the photocatalytic filter (η_{PF} is replaced by η_{UV} when the system is illuminated with no photocatalytic filter present), which can be expressed as the following equation:

$$\eta_{PF} = \frac{(C_{up} - C_{down})}{C_{up}} \quad (4)$$

where C_{up} ($= R_r C$) and C_{down} (ppm) are the upstream and downstream VOC concentrations, respectively. The value of η_{PF} would vary with the VOC concentration if the PCO reaction rate fits the Langmuir-Hinshelwood rate form, which is the most reported rate form for PCO kinetics.^{5-7,9,24} To simplify this problem, it was assumed that the PCO reaction fits the first-order reaction rate form,^{8,25} and this assumption was authenticated in the experiments. Thus, the VOC removal efficiency of the photocatalytic filter (η_{PF}) could be treated as a constant. Consequently, the general solution of eq 3 is:

$$C = C_0 \exp \left[-\frac{Q}{V} (1 + R_r \eta_{PF} - R_r) t \right] \quad (5)$$

where C_0 is the initial VOC concentration in the chamber.

In this study, the natural decay constant (K_n) was defined as the first-order decay constant of VOCs concentrations in the chamber when the UV lamp was off. The decay constant (K_a) was defined as the first-order K_a of the VOCs concentration, whereas the photocatalytic filter was illuminated with the UV light. According to eq 5, the K_a and K_n are $K_a = (1 + R_r \eta_{PF} - R_r)Q/V$ and $K_n = (1 + R_r)Q/V$, respectively. The K_a and K_n were also used to describe the first-order decay of VOC concentration, when the system is illuminated by UV light without photocatalytic filter present and runs in the dark with no photocatalytic filter present, respectively.

Ka for Real System Application

The K_a of VOC concentrations developed in this study need to be transferred to more applicable parameters (e.g., clean air delivery rate [CADR] or removal efficiency) before being applied in a real system. The CADR was first defined as the volume of filtrated air delivered by the air cleaners. Here, the CADR represents the volume of filtrated air passing through the photocatalytic filter per unit time, and it can be expressed as the following equation:

$$\text{CADR} = (K_a - K_n)V \quad (6)$$

where CADR is relevant to the VOCs removal efficiency of the photocatalytic filter and the airflow rate passing through the photocatalytic filter. The relationship between the CADR and the VOC removal efficiency of the photocatalytic filter can be described as the following equation:

$$\text{CADR} = R_r \eta_{PF} Q = R_r \eta_{PF} A v \quad (7)$$

where A is the filtration area of the photocatalytic filter, and v is the face velocity. Dividing eq 7 by the filtration area of the photocatalytic filter:

$$\frac{\text{CADR}}{A} = R_r \eta_{PF} v \quad (8)$$

Equation 8 represents the CADR per unit area (CADR/A) of the photocatalytic filter. This parameter can be applied to evaluate the CADR of an interested real system.

Effect of RH

Figure 4 shows the K_a of the toluene concentration with photocatalytic filter present under the RH of 30%, 50%, and 70%, which represent the dry, medium, and humid environmental conditions, respectively. The K_n under RH of 30%, 50%, and 70% ranged from 0.248 to 0.250 hr⁻¹, and the K_a varied from 0.34 to 0.381 hr⁻¹. The K_a rose 12.1%, when the RH increased from 30% to 70%. As shown in Figure 6, the values of the CADR, the CADR/A,

Figure 4. Effect RH on the K_a of the toluene concentrations with the photocatalytic filter (a) RH = 30%, (b) RH = 50%, and (c) RH = 70%.

and the η_{PF} for toluene increased with RH. The ozone concentration in the chamber was <25 ppb and was very close to the background ozone concentration. Under this condition, the toluene-ozone (O_3), UV/ O_3 , and UV/ O_3 /TiO₂ reaction rates were much slower than the UV/TiO₂ reaction rate. Therefore, the toluene removal resulted mainly from the photocatalytic filter (UV/TiO₂) instead of from the toluene- O_3 , UV/ O_3 , or UV/ O_3 /TiO₂ reaction.

Figure 5 shows the K_a s of the toluene concentration with no photocatalytic filter present under RH of 30%, 50%, and 70%, respectively. The Kn ranged from 0.248 to 0.249 hr⁻¹, and the K_a ranged from 0.260 to 0.263 hr⁻¹. The increase of RH has an insignificant effect on the removal of toluene by UV light. The ozone concentration in the chamber was <25 ppb. Therefore, the toluene- O_3 , UV/ O_3 , and UV/ O_3 /TiO₂ reaction rates were very slow under this condition. The removal of toluene was caused by direct gas-phase photolysis.

As shown in Table 2, the Kn and K_a of the formaldehyde concentration with photocatalytic filter present under RH of 30%, 50%, and 70% ranged from 0.247 to 0.249 hr⁻¹ and from 0.421 to 0.433 hr⁻¹, respectively. When the RH increased from 30% to 70%, the K_a rose 2.85%. The values of the CADR, the CADR/A, and the η_{PF} for formaldehyde also increased with RH, as shown in Figure 6.

The K_a of the formaldehyde concentration without photocatalytic filter present under RH of 30%, 50%, and

70% ranged from 0.247 to 0.248 hr⁻¹. When the system was illuminated by UV light, the K_a ranged from 0.315 to 0.316 hr⁻¹. The effect of RH on the formaldehyde removal by UV light was insignificant. The ozone concentration in the chamber was <25 ppb. The toluene- O_3 , UV/ O_3 , and UV/ O_3 /TiO₂ reaction rates were very slow under this condition. The removal of formaldehyde resulted mainly from direct gas-phase photolysis.

The result above demonstrates that the increase of RH has a positive effect on the effectiveness of the photocatalytic filter for removing toluene and formaldehyde. A possible explanation for this result is that the increase of RH can enhance the formation of hydroxyl radical. When an electron on the valence band (VB) of photocatalyst absorbs a photon with energy higher than the band gap between the VB and the conduction band (GB), it will be promoted to the GB, and, thus, an electron-hole pair (e^- and h^+) is created. The water molecule adsorbed on the surface of the photocatalyst will be oxidized to hydroxyl radicals by the holes (h^+). Hydroxyl radicals are the major free radicals attacking and decomposing VOC molecules.^{8,22}

When the RH increased from 30% to 70%, the values of the CADR, the CADR/A, and the η_{PF} for toluene increased ~46%. However, the values of the CADR, the CADR/A, and the η_{PF} for formaldehyde increased merely ~6.4%. The enhancement effect of RH on the effectiveness of a photocatalytic filter for removing formaldehyde

Figure 5. Effect of RH on the K_a of the toluene concentrations without the photocatalytic filter (a) RH = 30%, (b) RH = 50%, and (c) RH = 70%.

Table 2. Summary of the experimental conditions, results, and calculated parameters.

VOC	Filter	RH (%)	ν (m/hr)	K_n (hr ⁻¹)	K_a (hr ⁻¹)	CADR (m ³ /hr)	CADR/A (m ³ /hr/m ²)	η_{PF}
Toluene	D-type	30	177	0.249	0.34	0.0466	32.3	0.364
		50		0.250	0.367	0.0599	41.5	0.468
		70		0.248	0.381	0.0681	47.2	0.532
Formaldehyde	D-type	30	177	0.248	0.421	0.0886	61.3	0.692
		50		0.247	0.424	0.0906	62.8	0.708
		70		0.249	0.433	0.0942	65.2	0.736
Toluene	D-type	70	177	0.248	0.381	0.0681	47.2	0.532
			266	0.374	0.553	0.0916	63.5	0.477
			355	0.498	0.694	0.100	69.5	0.392
			444	0.627	0.828	0.103	71.3	0.332
			532	0.747	0.945	0.101	70.2	0.264
Formaldehyde	D-type	70	177	0.249	0.433	0.0942	65.2	0.736
			266	0.376	0.609	0.119	82.6	0.621
			355	0.501	0.753	0.129	89.4	0.504
			444	0.627	0.881	0.130	90.1	0.406
			532	0.749	1.01	0.134	92.5	0.348
Toluene	D-type	70	177	0.249	0.381	0.0676	46.8	0.528
				0.247	0.410	0.0835	57.8	0.652
				0.251	0.415	0.0840	58.1	0.656
Formaldehyde	D-type	70	177	0.248	0.433	0.0947	65.6	0.740
				0.247	0.390	0.0732	50.7	0.572
				0.250	0.414	0.0840	58.1	0.656

Figure 6. The relation between VOC removal efficiency with and without the photocatalytic filter (η_{PF} and η_{UV}) and RH, CADR and RH, and CADR/A and RH.

was weaker than that for removing toluene. This may result from the different hydrophilicities between formaldehyde and toluene and the competitive interaction between VOCs and water molecules for the adsorption site on the surface of a photocatalyst. In the presence of humidity, the surface of titania photocatalysts is hydroxylated, and hydroxyl groups are formed. A water molecule could be adsorbed on these hydroxyl groups via hydrogen bonding. By forming the $\text{OH} \cdots \pi$ electron type interaction, toluene could also be adsorbed on the same hydroxyl groups. Because water and toluene are adsorbed on the same hydroxyl groups, there may be a competitive interaction between water and toluene adsorbed. Formaldehyde is more polar than toluene. Like water, formaldehyde is supposedly adsorbed on the hydroxyl groups on the surface of the photocatalyst via hydrogen bonding.^{6,8} Thus, the competitive interaction between formaldehyde and water is probably stronger than that between toluene and water. The positive effect of RH on the PCO reaction rate by enhancing the formation of hydroxyl radical is partially counteracted by the negative effect of the competitive interaction between water and VOCs.

Effect of Air Change Rate

The Kns and the Kas of toluene with a photocatalytic filter present under different total air change rates are listed in Table 2. The values of the η_{PF} decrease with the increase of the face velocity, which is proportional to the total air change rate, as shown in Figure 7. This result shows that the effectiveness of the photocatalytic filter to remove VOCs decreases with the total air change rate.

The Kn and the Ka of the toluene concentration without a photocatalytic filter present under different total air change rates are listed in Table 3. The values of the η_{UV} decrease with the increase of face velocity, as shown in Figure 7. The experimental results of different total air change rates for formaldehyde were similar to that for toluene.

Figure 7 demonstrates the relation between η_{PF} and v (face velocity), CADR and v , and CADR/A and v . The VOC removal efficiency of the photocatalytic filter, η_{PF} , shows a linear negative relationship with face velocity within the face velocity range of ~ 177 – 532 m/hr. According to

Figure 7, the regression of η_{PF} for toluene and formaldehyde on the face velocity (v) can be presented as the following equations:

$$\eta_{PF}(\text{dimensionless}) = -0.000771(\text{hr/m}) \times v(\text{m/hr}) + 0.67 \quad (\text{for toluene}) \quad (9)$$

$$\eta_{PF}(\text{dimensionless}) = -0.00112(\text{hr/m}) \times v(\text{m/hr}) + 0.919 \quad (\text{for formaldehyde}) \quad (10)$$

Figure 7. (a) Relation between VOC removal efficiency with and without photocatalytic filter (η_{PF} and η_{UV}) and face velocity (v); (b) Relation between CADR and v and CADR/A and v .

Table 3. Summary of the experimental conditions, results, and calculated parameters.

VOC	Filter	RH (%)	ν (m/hr)	Kn (hr ⁻¹)	Ka (hr ⁻¹)	CADR (m ³ /hr)	CADR/A (m ³ /hr/m ²)	η_{uv}
Toluene	None	30	177	0.249	0.261	0.0061	4.25	0.048
		50		0.249	0.260	0.0056	3.90	0.044
		70		0.248	0.263	0.0077	5.32	0.060
Formaldehyde	None	30	177	0.247	0.304	0.0292	20.2	0.228
		50		0.247	0.307	0.0307	21.3	0.240
		70		0.248	0.306	0.0297	20.6	0.232
Toluene	None	70	177	0.248	0.263	0.0077	5.32	0.060
			266	0.374	0.394	0.0102	7.09	0.053
			355	0.498	0.517	0.0097	6.74	0.038
			444	0.627	0.643	0.0082	5.67	0.026
			532	0.749	0.77	0.0108	7.45	0.028
Formaldehyde	None	70	177	0.248	0.306	0.0297	20.6	0.232
			266	0.375	0.442	0.0343	23.8	0.179
			355	0.500	0.578	0.0399	27.7	0.156
			444	0.627	0.7	0.0374	25.9	0.117
			532	0.748	0.833	0.0435	30.1	0.113

To convert the unit of ν (m/hr) into a dimensionless unit, the unit of the coefficient was set in front of the ν as hr/m. Substituting eqs 9 and 10 into eq 8, respectively, we have:

$$\frac{\text{CADR}}{A} = R_t \times \nu [-0.000771(\text{hr/m}) \times \nu(\text{m/hr}) + 0.67] \text{ (for toluene)} \quad (11)$$

and

$$\frac{\text{CADR}}{A} = R_t \times \nu [-0.00112(\text{hr/m}) \times \nu(\text{m/hr}) + 0.919] \text{ (for formaldehyde)} \quad (12)$$

The PCO reaction rate in this study can be defined as:

$$r = (C_{\text{up}} - C_{\text{down}})Q/A = C_{\text{up}}\eta_{\text{PF}}\nu = R_t C \eta_{\text{PF}} \nu \quad (13)$$

which is very similar to CADR/A (See eq 8). Therefore, CADR/A can be considered as a kind of PCO reaction rate independent of VOC concentration. As shown in Figure 7 and eqs 11 and 12, CADR/A is a function of face velocity. In heterogeneous catalytic reaction, the apparent reaction rate is dependant on the gas-phase mass-transfer rate (increases with face velocity), surface reaction rate (independent of face velocity), or both of them. The effect of gas-phase mass transfer from the bulk phase to the surface of photocatalytic filter decreased with face velocity increasing. When the face velocity is >444 m/hr, the effect of mass transfer is no longer important.

The face velocities used in these experiments are lower than those in typical HVAC systems. The Reynolds numbers calculated from the configuration of the experimental system range from 51.4 to 154.6, which are smaller than those of typical HVAC systems (>2100). Therefore, the experimental system of this study is under a laminar flow condition, and typical HVAC systems are

under a turbulent flow condition. The gas-phase mass-transfer rates in typical HVAC systems are faster than those in this experimental system. Because the CADR/A asymptotically reaches the upper limit at face velocity of 444 m/hr, and this value corresponds with the real surface reaction rate, the CADR/A in typical HVAC systems remains as expected.

Effect of Different Types of Photocatalytic Filters

The Kn and the Ka of the toluene concentration in the chamber equipped with D-type, K-type, and Degussa P25 photocatalytic filters are shown in Table 2. The effectiveness of the Degussa P25 photocatalytic filter for removing toluene was the best among the three photocatalytic filters tested, and the next was the K-type photocatalytic filter. The values of CADR, CADR/A, and η_{PF} of the three photocatalytic filters ranged from 0.0676 to 0.084 m³/hr, 46.8 to 58.1 m³/hr per m², and 0.528 to 0.659 m³/hr, respectively.

The Kn and the Ka of the formaldehyde concentration in the chamber equipped with D-type, K-type, and Degussa P25 photocatalytic filters are listed in Table 2. The effectiveness of the D-type photocatalytic filter to remove formaldehyde was the best, and the next was the Degussa P25 photocatalytic filter. The values of CADR, CADR/A, and η_{PF} of the three photocatalytic filters tested ranged from 0.0732 to 0.0947 m³/hr, 50.7 to 65.6 m³/hr per m², and 0.572 to 0.74 m³/hr, respectively. The VOC removal efficiency (η_{PF}), CADR, and CADR/A of the photocatalytic filters vary with the filter types, and the relevant mechanism needs further research.

CONCLUSIONS

According to the experimental results, photocatalytic filters are capable of controlling VOC contaminations in HVAC systems. The Kns of VOCs are dependent on the total air change rates, whereas the Kas are affected by air change rates (face velocity), RH, and photocatalytic filter types. The VOC removal efficiency of the photocatalytic

filters increases with RH but decreases with filtration face velocity. However, the CADR increases with face velocity and reaches the upper limit at a face velocity of 444 m/hr. CADR/A of the photocatalytic filter can be used to upscale the system, because this value corresponds with the real surface reaction rate when face velocity is >444 m/hr. The effectiveness of the photocatalytic filters to control VOCs varies with filter types, and the relevant mechanism needs further research.

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