

# Ozone removal by HVAC filters

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## Abstract

Residential and commercial HVAC filters that have been loaded with particles during operation in the field can remove ozone from intake or recirculated air. However, knowledge of the relative importance of HVAC filters as a removal mechanism for ozone in residential and commercial buildings is incomplete. We measured the ozone removal efficiencies of clean (unused) fiberglass, clean synthetic filters, and field-loaded residential and commercial filters in a controlled laboratory setting. For most filters, the ozone removal efficiency declined rapidly but converged to a non-zero (steady-state) value. This steady-state ozone removal efficiency varied from 0% to 9% for clean filters. The mean steady-state ozone removal efficiencies for loaded residential and commercial filters were 10% and 41%, respectively. Repeated exposure of filters to ozone following a 24-h period of no exposure led to a regeneration of ozone removal efficiency. Based on a theoretical scaling analysis of mechanisms that are involved in the ozone removal process, we speculate that the steady-state ozone removal efficiency is limited by reactant diffusion out of particles, and that regeneration is due to internal diffusion of reactive species to sites available to ozone for reaction. Finally, by applying our results to a screening model for typical residential and commercial buildings, HVAC filters were estimated to contribute 22% and 95%, respectively, of total ozone removal in HVAC systems. © 2006 Elsevier Ltd. All rights reserved.

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## 1. Introduction

Research has shown that, on average, Americans spend more than 90% of their time indoors (Robinson and Nelson, 1995). Consequently, exposure to air pollutants is often greater indoors than outdoors, even when outdoor concentrations are higher, as is typically the case with ozone. Weschler et al. (1989) reasoned that indoor exposures to ozone may represent a significant fraction of total

exposure. Thus, it is important to understand both the sources and sinks of ozone in residential and commercial buildings.

Heating, ventilating, and air conditioning (HVAC) systems contain many components (e.g., ducts, filters, cooling coils, fans) that can serve as reactive sinks for ozone. These components are likely varied in their overall contribution to ozone removal. For example, HVAC ducts were shown to remove less than 4% of ozone passing through them, with considerably less removal on unlined ducts (Morrison et al., 1998), while HVAC filters have been found to remove significantly more ozone, e.g., up to 36% at steady state (Hyttinen et al., 2003, 2006; Bekö et al., 2005, 2006).

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The removal of ozone from indoor environments is generally desirable. However, its removal by reactions with HVAC filters can lead to oxidation products such as formaldehyde and other carbonyls, formic acid, and ultrafine particles (Bekö et al., 2005; Hyttinen et al., 2006). Hyttinen et al. (2006) observed the production of formaldehyde and formic acid when ozone reacted with commercial HVAC filters, particularly at the beginning of ozone exposure. Bekö et al. (2005) observed higher ultrafine particle counts downstream of filters relative to upstream counts in the presence of ozone. Hyttinen et al. (2003) reported increased odor intensity downstream of a pre-filter that had been exposed to ozone. Schleibinger and Rüden (1999) observed significant increases in formaldehyde and acetone downstream of filters in one HVAC system, but did not report ozone concentration data. Bekö et al. (2006) found that air from filters exposed to ozone had a lower acceptability when presented to an untrained panel of subjects.

The fractional removal efficiency ( $\eta$ ) of ozone across an HVAC filter is defined as

$$\eta = 1 - \frac{C_d}{C_u}, \quad (1)$$

where,  $C_d$  and  $C_u$  are the downstream and upstream ozone concentrations (ppb), respectively. The ozone removal efficiency of HVAC filters appears to decay with time (Bekö et al., 2005, 2006; Hyttinen et al., 2006). However, Bekö et al. (2006) observed a regeneration of ozone removal efficiency after filters were isolated from ozone and treated with clean air, nitrogen, and/or heat. They hypothesized that VOCs inside the bulk particle volume slowly diffuse to the external surface following reactions of surface sites with ozone.

In this paper we present ozone removal efficiencies for several residential and commercial filters and use a magnitude analysis to investigate the importance of processes involved in the removal of ozone. These results are extended to a screening model of typical buildings to estimate the importance of ozone removal on filters.

## 2. Methods

### 2.1. Experimental system

Fig. 1 depicts the experimental system used to determine ozone removal efficiencies. A dual-section electro-polished stainless steel chamber

(28.3 L per section) was separated by a test filter. Small fans were used to mix the air in each section. All air which passed through the HVAC filter was pre-filtered through a polytetrafluoroethylene (PTFE) filter with a pore size of 2.0  $\mu\text{m}$  in order to keep particles from depositing on the sample filter. Room air was pulled through a vacuum pump with fixed volumetric flow rate and was mixed with ozone generated by a corona-based ozone generator (Prozone, Model PZ 6 Air). The mixed air was then conveyed through the chamber system (into the top chamber, through the filter, out of the bottom chamber). The air flow rate of 20  $\text{L min}^{-1}$  through the filter was confirmed after each experiment with a bubble flow meter (Sensidyne, Model Gilibrator 2) at the outlet of the bottom chamber, as shown in Fig. 1. The face velocity through the filter was 0.4  $\text{cm s}^{-1}$ , and was selected based on equipment limitations.

Ozone concentrations upstream and downstream of the filter were alternately monitored and recorded in 3 min periods early in an experiment and then 3 min upstream and 10 min downstream after 30 min by a calibrated UV ozone analyzer (2B Technologies, Model 202). The ozone concentration upstream was approximately 80 ppb for most experiments. A flow controller was used to switch between top and bottom chambers for purposes of ozone measurement. The temperature and relative humidity during each experiment was monitored with a temperature and RH sensor connected to a datalogger (Energy Conservatory APT data logger).

### 2.2. Test filters

Properties of the test filters are presented in Table 1. A total of eight clean (unused) and 14

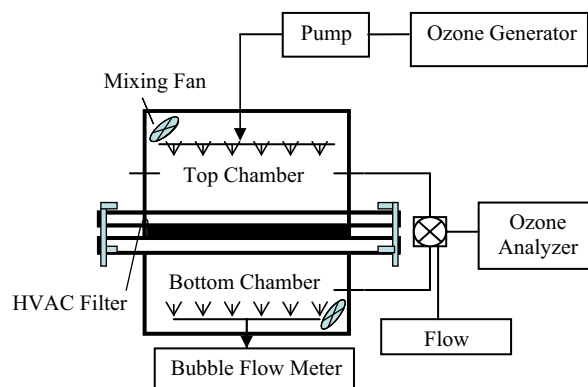


Fig. 1. Schematic of experimental system.

loaded (used) filters were tested. Eight loaded filters were obtained from residential HVAC systems (R1–R8). Six loaded filters were obtained from commercial HVAC systems (C1–C6). The test filters were either composed of spun fiberglass or synthetic materials commonly used in residential and commercial HVAC systems. The eight clean filters included two synthetic filters (CL1, CL2) manufactured by the same company as the other used commercial filters tested in this study, three synthetic filters (CL3–CL5) made by a different manufacturer, and three identical fiberglass filters (CL6–CL8). When characterized by ASHRAE Standard 52.2 (1999), the filters had a minimum efficiency rating value (MERV) of 4 or less, with the exception of filter C6 which had a MERV value of 8. All filters had a porosity of greater than 99% as measured by submerging a known volume of bulk filter into a beaker of water and measuring the volume change.

### 2.3. Standard and regeneration experiments

Clean filters were exposed to ozone for 5 h and used filters for 12 h. Immediately after the initial exposure, seven of the 14 filters (R3, R4, R5, R7, C1, C2, C3) were sealed in aluminum foil for 24 h, and then subjected to a second ozone exposure for

5 h at an ozone concentration of approximately 80 ppb. Three of these seven filters (R3, R7, C1) were removed a second time and sealed in aluminum foil for 72 h after the second exposure to ozone. These three filters were then subjected to a third exposure for 5 h at an ozone concentration of approximately 80 ppb. As the experimental protocol was refined, there were two deviations from the procedure defined above. Filters R1 (first exposure) and R2 (first exposure) were exposed to higher levels of ozone, approximately 500 and 250 ppb, respectively. Also, for filters R1 and R2 two ozone monitors were used, instead of one, to continuously measure the concentrations in the top and bottom sections of the test apparatus.

## 3. Results and discussion

### 3.1. Results

The air temperature ranged from 22 to 26 °C and the relative humidity ranged from 45% to 60% for all experiments. The fractional removal efficiency of ozone as a function of time is presented in Fig. 2. A clean fiberglass filter (CL8) exposed once, a clean synthetic filter (CL5) exposed once, a loaded residential (fiberglass) filter (R4) exposed twice

Table 1  
Properties of test filters

Filter	Material	Thickness (cm)	In field (weeks)	MERV rating	Operation location
CL1	Synthetic	2.5	0	4	N/A
CL2	Synthetic	2.5	0	4	N/A
CL3	Synthetic	2	0	4	N/A
CL4	Synthetic	2	0	4	N/A
CL5	Synthetic	2	0	4	N/A
CL6	Fiberglass	2.75	0	<4	N/A
CL7	Fiberglass	2.75	0	<4	N/A
CL8	Fiberglass	2.75	0	<4	N/A
R1	Fiberglass	2.75	4	<4	Residential
R2	Fiberglass	2.75	12	<4	Residential
R3	Synthetic	2	4–6	4	Residential
R4	Fiberglass	2.75	12	<4	Residential
R5	Synthetic	4	4–6	4	Residential
R6	Synthetic	2.2	4–6	4	Residential
R7	Fiberglass	2.75	12	<4	Residential
R8	Fiberglass	2.75	12	<4	Residential
C1	Synthetic	5	4–6	4	Commercial
C2	Synthetic	2	4–6	4	Commercial
C3	Synthetic	5	4–6	4	Commercial
C4	Synthetic	4	4–6	4	Commercial
C5	Synthetic	2.5	4–6	4	Commercial
C6	Synthetic	2.5	4	8	Commercial

and a loaded commercial (synthetic) filter (C1) exposed three times are presented here as examples. For clean fiberglass and synthetic filters, the ozone removal efficiency dropped rapidly in the first 30–60 min, and converged to an approximate steady-state value during the following 4 h. Amongst the clean filters, two synthetic filters did not remove any ozone, three synthetic filters from a different manufacturer removed, on average, 8% of ozone at steady state, and three fiberglass filters removed, on average, 3% of ozone at steady state. It is not clear whether the steady-state removal efficiencies were due to ozone reactions with the filter material or catalytic decomposition of ozone. However, it does appear that ozone consumption across clean HVAC filters varies for filters made of different materials, as well as from different manufacturers, a result similar to that reported by Hyttinen et al. (2006).

As shown in Fig. 2, ozone removal was greater for loaded filters than for clean filters. Generally, ozone reduction was greatest at the beginning of each exposure test, and then decreased until a steady-state removal efficiency was reached. A comparison of results for clean and loaded filters suggests that ozone removal is mainly due to the reaction between ozone and particles, rather than the filter material.

Ozone removal capacity was regenerated following a period of filter isolation from ozone and air flow. The results of repeated experiments on the same filters after 24 h of isolation indicated a brief initial regeneration of ozone removal efficiency, followed by a decrease in ozone removal efficiency to a value similar to that at the end of the first exposure. Although Filter C1 was exposed to ozone for a third time, it did not exhibit any significant regeneration.

Approximate steady-state ozone removal efficiencies for each used filter are presented in Fig. 3. The error bars indicate the uncertainty calculated from the accuracy of the ozone monitors (the greater of 1.5 ppb or 2%). When identical clean filters were tested, the average result is reported. Commercial filters generally removed more ozone than residential filters due to differences in particle loading, operation time, materials, and types of filters. For the eight residential filters, final ozone removal efficiencies ranged from 5% to 14%, with an average of 10% for the first ozone exposure. The steady-state ozone removal efficiencies for each ozone exposure were similar for Filters R3, R4, and R5. Filter R7 removed much more ozone during its second and third ozone exposures than it did during its first exposure. Unlike other filters in the study, Filter R7 was stored in an outdoor

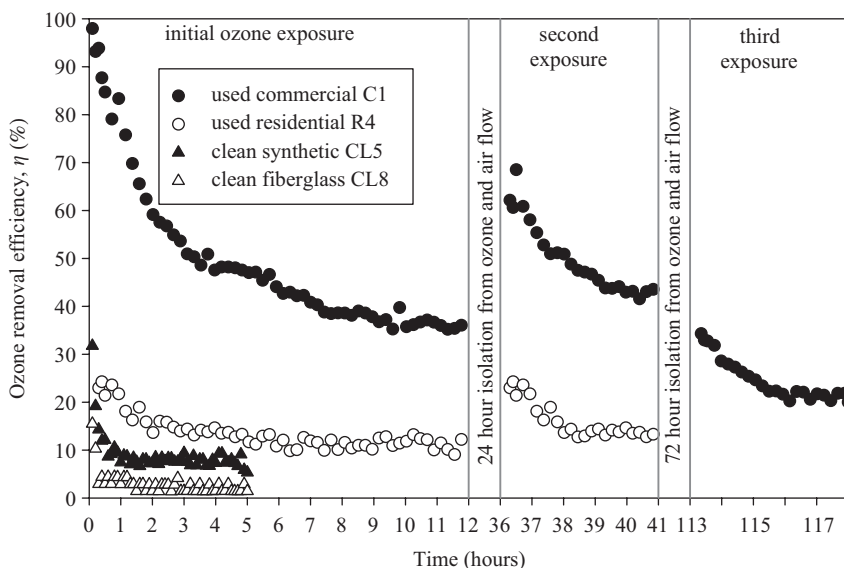


Fig. 2. Ozone removal efficiency for a loaded commercial synthetic filter (C1), a loaded residential fiberglass filter (R4), a clean synthetic filter (CL5), and a clean fiberglass filter (CL8). Samples C1 and R4 were exposed to 80 ppb of ozone for 12 h, stored for 24 h without exposure, and exposed again for a 5 h period at 80 ppb. Sample C1 was then stored again for 72 h with no exposure to ozone and then subjected to a third exposure of 80 ppb for 5 h. Samples CL5 and CL8 were exposed to 80 ppb ozone for 5 h.

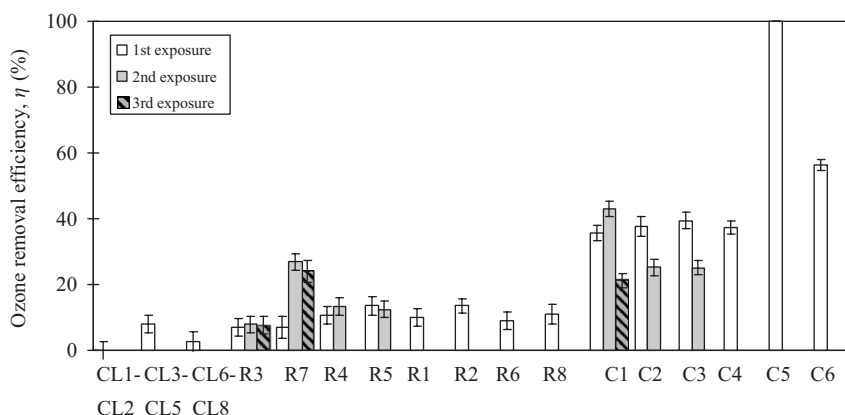


Fig. 3. Approximate steady-state ozone removal efficiency for used residential and commercial filters, as well as clean synthetic (CL1–CL5) and clean fiberglass (CL6–CL8) filters. Results obtained for filters CL1–CL2 (synthetic), CL3–CL5 (synthetic, different manufacturer), and CL6–CL8 (fiberglass) were, respectively, averaged.

environment before being delivered to the laboratory and may have been contaminated, but we have no hypothesis for the diminished initial ozone removal.

For five commercial filters (C1–C4, C6), the final ozone removal efficiencies ranged from 35% to 55%, with an average of 41% for the first ozone exposure. The ozone removal efficiency of 100% for Filter C5 was likely due to a large amount of unsaturated organic compounds on the filter, as the filter was taken from a restaurant and was visibly coated with grease. This filter was excluded from the averages reported here. Even after excluding Filter C5, the mean ozone removal efficiency for commercial filters was statistically greater than the mean removal efficiency for residential filters ( $\alpha = 0.05$ ).

The steady-state ozone removal efficiencies for the first and second ozone exposures were similar for Filters C1, C2, and C3. Filter C1 removed much less ozone in the third ozone exposure than the previous exposures. It is possible that easily reacted compounds were depleted in this filter during the previous two exposures.

### 3.2. Analysis of ozone removal based on time scales

To further explore the experimental results, we conducted a magnitude analysis on the ozone removal processes. Processes involved in the removal of ozone on HVAC filters include: (1) ozone advection through the filter, (2) ozone diffusion into the boundary layer near particles, (3) ozone diffusion into particles, (4) diffusion of reactive organic compounds out of particles, (5) ozone reactions

with reactive organic compounds, and (6) ozone catalysis on filter components. To better understand how each process affects ozone removal to HVAC filters, we analyzed each of these processes using a time-scale analysis, the results of which are summarized in Table 2.

For advection (Process 1), assumptions were made regarding the thickness of the filter and velocity of air flowing through the filter as shown in Table 2. In a typical HVAC system, the magnitude of the corresponding time scale is  $10^{-2}$  s. In our experimental system, the time scale for advection was two orders of magnitude greater owing to the smaller face velocity in the experimental apparatus. For actual systems and the experimental system, it does not appear that advection is/was a limiting factor for ozone removal.

For ozone diffusion to particles (Process 2), the time scale is approximately  $10^{-8}$  s, short enough not to be a limiting transport process, e.g., relative to advection. We also explored ozone diffusion into (Process 3) and oleic acid, a representative reactant, diffusion out of (Process 4) five different types of particles: diesel soot, oleic acid aerosol, polyoxymethylene aerosol, coke aerosol, and activated carbon particles. We chose these types of particles based on information available in the literature as well as relevance to aerosols that may collect on HVAC filters. The approximate time scales for ozone diffusion varied significantly between type of particle, with the smallest value for oleic acid ( $10^{-2}$  s) and greatest value for diesel soot ( $10^6$  s). Similarly, the time scales for oleic acid diffusion

Table 2  
Time scaling analysis for each ozone removal process

Process	Equation	Condition/particle composition	Assumptions	Source	Time scale magnitude (s)
(1) Advection	$t = \frac{\delta}{v}$	HVAC system	$v = 10^2 \text{ cm s}^{-1}$	ASHRAE (1999)	$10^{-2}$
(2) Ozone diffusion through boundary layer	$t = \frac{\delta_1^2}{D}$	Experimental	$v = 0.8 \text{ cm s}^{-1}$	Shepherd (1965)	$10^0$
(3) Ozone diffusion into particle <sup>a</sup>	$t = \frac{d_p^2}{D_{\text{eff}}}$	N/A	$\delta_1 = 0.3 \mu\text{m}$		$10^{-8}$
		Diesel soot <sup>b</sup>	$D = 0.14 \text{ cm}^2 \text{ s}^{-1}$	Massman (1998)	
			$D_{\text{eff}} = 2 \times 10^{-15} \text{ cm}^2 \text{ s}^{-1}$	Odum et al. (1994)	$10^6$
		Oleic acid <sup>c</sup>	$D_{\text{eff}} = 1 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$	Smith et al. (2002)	$10^{-2}$
(4) Oleic acid diffusion out of particle <sup>a</sup>	$t = \frac{d_p^2}{D_{\text{eff}}}$	Polyoxymethylene	$D_{\text{eff}} = 4 \times 10^{-11} \text{ cm}^2 \text{ s}^{-1}$	Ahn et al. (2005)	$10^2$
		Coke	$D_{\text{eff}} = 2 \times 10^{-12} \text{ cm}^2 \text{ s}^{-1}$	Ahn et al. (2005)	$10^3$
		Activated carbon	$D_{\text{eff}} = 6 \times 10^{-12} \text{ cm}^2 \text{ s}^{-1}$	Ahn et al. (2005)	$10^3$
		Diesel soot <sup>b</sup>	$D_{\text{eff}} = 1 \times 10^{-15} \text{ cm}^2 \text{ s}^{-1}$	Odum et al. (1994)	$10^7$
		Oleic acid <sup>d</sup>	$D_{\text{eff}} = 9 \times 10^{-10} \text{ cm}^2 \text{ s}^{-1}$	Smith et al. (2002)	$10^1$
		Polyoxymethylene	$D_{\text{eff}} = 2 \times 10^{-11} \text{ cm}^2 \text{ s}^{-1}$	Ahn et al. (2005)	$10^3$
		Coke	$D_{\text{eff}} = 1 \times 10^{-12} \text{ cm}^2 \text{ s}^{-1}$	Ahn et al. (2005)	$10^4$
		Activated carbon	$D_{\text{eff}} = 3 \times 10^{-12} \text{ cm}^2 \text{ s}^{-1}$	Ahn et al. (2005)	$10^3$
(5) Ozone reaction with different materials <sup>h</sup>	$v_s = \frac{\gamma \langle v \rangle}{4}$ $t = \frac{2\lambda^*}{3v_s}$	Oleic acid	$\gamma = 8 \times 10^{-4}$	Moise and Rudich (2002)	$10^{-6}$
		Clean fiberglass <sup>e</sup>	$\gamma = 10^{-7}$	Liu and Nazaroff (2001)	$10^{-3}$
		Fractal carbon soot	$\gamma = 10^{-7}$	Kamm et al. (1999)	$10^{-3}$
		Candle soot <sup>f</sup>	$\gamma = 7.5 \times 10^{-6}$	Ilin et al. (1991)	$10^{-4}$
		Activated carbon	$v_s = 0.19 \text{ cm s}^{-1}$	Grontoft (2002)	$10^{-5}$
		Spark soot <sup>g</sup>	$\gamma = 2.9 \times 10^{-11}$	Kamm et al. (2004)	$10^1$
		Saharan sand	$\gamma = 6.1 \times 10^{-6}$	Michel et al. (2003)	$10^{-4}$
		SiO <sub>2</sub>	$\gamma = 1.4 \times 10^{-6}$	Il'in et al. (1991)	$10^{-4}$
		NaCl	$\gamma = 1.6 \times 10^{-6}$	Il'in et al. (1991)	$10^{-4}$
		Water	$\gamma = 6.6 \times 10^{-7}$	Il'in et al. (1991)	$10^{-4}$

In this table,  $t$  is time scale,  $\delta$  is filter thickness,  $v$  is air flow velocity,  $\delta_1$  is boundary layer thickness,  $D$  is diffusivity,  $d_p$  is particle diameter,  $D_{\text{eff}}$  is effective diffusivity,  $v_s$  is surface deposition velocity,  $\gamma$  is surface reaction probability,  $\langle v \rangle$  is Boltzmann velocity, and  $\lambda^*$  is the mean free path of air. The assumptions and constants used in this analysis include:  $\delta = 2.5 \text{ cm}$ ,  $d_p = 1 \mu\text{m}$ ,  $\lambda^* = 0.065 \mu\text{m}$ , and  $\langle v \rangle = 360 \text{ m s}^{-1}$ .

<sup>a</sup> $D_{\text{eff}}$  (effective diffusivity) was calculated from the diffusivity of pyrene by using the following approximate relationship:  $(D_{\text{eff}})_a / (D_{\text{eff}})_b = (MW_a / MW_b)^{-1/2}$  (Thibodeaux, 1996).

<sup>b</sup>Fresh diesel aerosol with organic liquid outer layer.

<sup>c</sup> $D_{\text{eff}}$  was calculated from oxygen diffusivity.

<sup>d</sup>Self-diffusion coefficient.

<sup>e</sup>Previously exposed to high ozone.

<sup>f</sup>Oxidized candle soot.

<sup>g</sup>Gasification of soot in 1% ozone.

<sup>h</sup>Equation  $t = 0.67\lambda^* / v_s$  was used based on Cano-Ruiz et al. (1993).

varied from  $10^1$  s for oleic acid to  $10^7$  s for diesel soot. The diesel aerosol was fresh and had a liquid organic layer on the exterior of the particle that likely acted as a barrier to diffusion (Odum et al., 1994). In a real HVAC system, fresh combustion particles would likely lose this outer barrier quickly because of volatilization. Ozone diffusion into particles is estimated to be 0–3 orders of magnitude faster than oleic acid diffusion out of particles. This suggests that ozone diffusion is not the only factor that limits transport/reactions within particles, and is often unimportant relative to diffusion of internal organic species.

Finally, we also estimate time scales for ozone reaction (Process 5) with several particles as listed in Table 2. The reaction rate with oleic acid is estimated to be the fastest ( $10^{-6}$  s) and spark soot the slowest (approximately 10 s). It is difficult to separate ozone catalysis (Process 6) from bimolecular reactions as these effects are often combined in published experimental data.

Based on the magnitude analysis described above, it appears that diffusion processes internal to particles deposited on the filter are the limiting factor for ozone removal in filters. Whether diffusion of ozone into particles, diffusion of reactive species out of particles, or both contribute significantly to resistance to ozone removal depends largely on the composition of deposited particles.

### 3.3. Analysis of experimental results

Ozone reactions with, or catalytic removal on, clean filters, appear to contribute only a small amount (0–25%) of total ozone removal on HVAC filters; reactions between ozone and deposited particles are responsible for most of the removal. The time for each loaded filter to reach approximate steady-state ozone removal is calculated to be on the order of  $10^4$  s. Of the processes described in Section 3.1, this time scale is most consistent with those for ozone diffusion into, and oleic acid diffusion out of, particles. The approximate steady-state removal efficiency for ozone might be a limiting value defined by diffusion processes. For example, it is conceivable that reaction sites on particle surfaces are consumed rapidly by ozone. This would establish a concentration gradient for reactive species diffusion from within particles toward the exterior surface. The extent of reactions at the surface might thus be limited by the rate of diffusion of species to the surface, or to the ozone which diffuses into the

particles. Continuous diffusion and thus continuous replenishing of filter surface with reactive species and their reactions with ozone may be responsible for steady-state ozone removal. Diffusion-limited processes might also explain the regeneration of ozone removal following the storage of filters in an ozone-free environment. During periods of low ozone exposure, reactants will diffuse outward to the particle surface, thus becoming easily available for reaction with ozone.

### 3.4. Estimation of ozone consumption on filter vs. duct in HVAC systems

A screening assessment was completed to explore the relative importance of ozone removal on HVAC filters, as compared to removal in the rest of the HVAC system. A series of simplifying assumptions were made for residential systems. These included: (1) treatment of the residential dwelling as a well-mixed reactor, (2) constant building recirculation rate, (3) constant ozone deposition loss rate, and (4) steady-state conditions. These assumptions yield

$$\eta_r = \frac{\beta_t - \beta_s}{\lambda_r}, \quad (2)$$

where  $\eta_r$  is the ozone removal efficiency in the entire HVAC system (–),  $\lambda_r$  is the building air recirculation rate ( $\text{h}^{-1}$ ), defined here as the volumetric flow rate through the HVAC system divided by the house volume, and  $\beta_s$  and  $\beta_t$  are the ozone deposition loss rates when the HVAC system is off and when it is operating ( $\text{h}^{-1}$ ), respectively. An implicit assumption in this analysis is that the difference in ozone loss rates ( $\beta_t - \beta_s$ ) is due entirely to reactions in the HVAC system. However, Mueller et al. (1973) described how increased air flow in the occupied space actually increases ozone removal at surfaces due to enhanced mass transfer to surfaces, a phenomenon supported by the work of Morrison et al. (2003). Thus, this assumption may cause an overestimation of the impact of HVAC system removal; the analysis described here should be regarded as an upper bound on ozone removal by residential filters.

Sabersky et al. (1973) reported that in a detached residential building,  $\beta_s$  was  $2.9 \text{ h}^{-1}$  without the HVAC system operating and  $5.4 \text{ h}^{-1}$  with the HVAC system operating. A typical house with a volume of  $377 \text{ m}^3$  was selected by considering the typical home floor area from the U.S. Bureau of the Census American Housing Survey (2001). The flow

through the air handler ( $Q_f$ ) was determined by assuming a continuously operated 3.5-ton air conditioner with a recommended HVAC flow rate of  $2040 \text{ m}^3 \text{ h}^{-1}$ .

Therefore, substituting values of  $\lambda_r$ ,  $\beta_s$ , and  $\beta_t$  and solving for  $\eta_r$  yields a value of 46%. It is assumed that the ozone reacts with the filter first (i.e., filter in the return grill—typical of houses in the U.S.) and then with the other HVAC components. Based on an average ozone removal efficiency of 10% for residential filters from our experiments, HVAC filters are predicted to remove approximately 22% (10% divided by 46%) of the total ozone removed by the entire residential HVAC system. Significant variations are expected around this value based on differences in model input parameters and assumptions, and actual filter conditions. However, the results presented here suggest that while filters contribute to ozone removal in residential HVAC systems, they are likely not the dominant sink for ozone removal.

A similar analysis was completed for commercial HVAC systems. Ozone-laden air first enters into the return duct (a combination of recirculated and fresh air), passes through the filter bank, and then passes through the supply duct system. To model this process we assumed plug flow and calculated the ozone loss in ducts with Eq. (3) and our experimental results for ozone removal across the filter with Eq. (4):

$$\frac{C}{C_0} = e^{-\eta_d A}, \quad (3)$$

$$\frac{C}{C_0} = 1 - \eta, \quad (4)$$

where  $C$  is the concentration leaving the component (ppb),  $C_0$  is the concentration entering the component (ppb),  $\eta_d$  is the ozone removal efficiency per unit area of duct ( $\text{m}^{-2}$ ), and  $A$  is the inside surface area of the duct ( $\text{m}^2$ ). A typical HVAC system was assumed as described by Sippola and Nazaroff (2003): 48 m of uninsulated return duct, followed by an HVAC filter, then 55 m of lined supply duct, total return duct area of  $117 \text{ m}^2$ , and total supply duct area of  $134 \text{ m}^2$ . Eq. (3) was first applied for the uninsulated return duct assuming a value for  $\eta_d$  of 0.02% per  $162 \text{ m}^2$  (Morrison et al., 1998), followed by Eq. (4) with  $\eta = 41\%$  based on the experimentally determined average ozone removal efficiency for a commercial filter, and Eq. (3) for the insulated

supply ducts with  $\eta_d$  of 4% per  $162 \text{ m}^2$  (Morrison et al., 1998).

The HVAC filter, supply duct, and return duct were predicted to contribute 95%, 4%, and <1% of the total ozone removed by the entire commercial HVAC system, respectively. Although this analysis neglects other HVAC components such as the cooling coil, this high contribution to ozone removal by the HVAC filter is intuitively reasonable, since HVAC filters are the most likely location for particle accumulation in commercial HVAC systems (Sippola and Nazaroff, 2003).

#### 4. Conclusions and recommendations for future research

Ozone is consumed while flowing through HVAC filters. This study involved eight residential and six commercial filters that were used in actual buildings and loaded with particles of both indoor and outdoor origin. The differences in ozone removal efficiency between these two types of filter applications were significant; the mean steady-state ozone removal efficiencies through residential and commercial HVAC filters were 10% and 41%, respectively. This difference was likely due to greater particle loading and longer operation time for commercial filters.

Ozone removal efficiency across clean HVAC filters varied for different filter materials, as well as different manufacturers. Removal efficiencies across clean filters were generally a small fraction of removal across loaded filters, particularly for commercial filters.

The ozone removal efficiency of HVAC filters can be partially to fully regenerated during periods of low ozone exposure. An order-of-magnitude time scaling analysis suggests that diffusion processes internal to particles are the limiting factors in terms of steady-state ozone removal efficiency on HVAC filters, as well as of the regeneration of their ozone removal abilities.

Additional research is needed to understand better the importance of ozone reactions with HVAC filters under actual operating conditions in buildings. In this study, the face velocity through each test filter was  $0.4 \text{ cm s}^{-1}$ , about 2 orders of magnitude lower than expected for filters in actual operating HVAC systems. Additional experiments are needed at higher face velocities to assess whether lower time scales for advection greatly affect the results described in this paper.

The laboratory experiments completed for this study did not include continuous particle deposition on test filters, contrary to what would be observed in actual HVAC systems. The replenishment of reaction sites through continuous particle deposition would presumably prolong the time required to reach a steady-state ozone removal efficiency, and additional research is warranted to explore this effect.

This study did not involve measurements of the byproducts associated with ozone reactions on filters. Additional research is needed to identify and quantify time-dependent emissions of oxidized products and their potential significance with respect to indoor air quality.

In addition to identifying the significance of ozone reactions on HVAC filters with respect to indoor air quality, an improved understanding of the fundamental processes involved with such reactions may allow for the development of improved HVAC filters that make use of such processes. For example, it may be possible to embed or coat filters with reactive materials to enhance ozone removal without significant formation of harmful reaction products. The authors hope that the work presented in this paper will facilitate future research to that end.

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