OZONE REMOVAL BY RESIDENTIAL HVAC FILTERS

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ABSTRACT

HVAC filters have a significant influence on indoor air quality. In addition to removing particulate contaminants, filters accumulate a particle layer that can react with ozone. Ozone-particle cake reactions serve as a sink for ozone and a source of secondary carbonyls. The location of filters in air distribution systems can lead to byproducts being distributed throughout a building. Two experiments were performed to determine the ozone removal efficiency on two residential filters that were loaded with particles for one month (#1) and three months (#2). On both filters, the ozone removal efficiency dropped rapidly during the first 30 minutes and then stayed approximately constant for 4 hours. The steady state values of ozone removal efficiency were 10% for Filter #1 and 14% for Filter #2 at a face velocity of 0.81 cm/s. The potential for HVAC filters to affect ozone concentrations in residential buildings was evaluated using a well-mixed reactor model. The tested filters reduced indoor ozone levels slightly when compared to indoor surfaces and an entire HVAC system, although the impact was much smaller than that of the air exchange rate. The influence of continuous particle deposition was not considered here, but would likely increase the impact of ozone interactions on HVAC filters.

INDEX TERMS

Ozone removal, HVAC filter, Modeling, Experiments, Air exchange rate

INTRODUCTION

Heating, ventilation, and air conditioning (HVAC) systems play an important role in providing comfort in residential, commercial, and institutional buildings. However, they also play a potentially significant role as conveyers and as sources of indoor air pollution (Pejtersen *et al.* 1989, Finke and Fitzner 1993, Batterman and Burge 1995). A higher incidence of sick-building syndrome has been observed among office workers in buildings with HVAC systems (Mendell and Smith 1990). The reasons for this observation are not entirely clear, but may include direct (primary) emissions of volatile organic compounds (VOCs) from HVAC components, growth and release of biological agents, and/or emissions of secondary pollutants resulting from heterogeneous chemistry that occurs on surfaces of the HVAC system.

Ozone, an oxidant and common indoor and outdoor pollutant, is of particular interest for surface reactions with HVAC components. Byproducts of ozone-surface reactions are likely to include carbonyls that might be irritating to the upper-respiratory system of building occupants. Morrison *et al.* (1998) observed that exposure to 100 ppb of ozone increased the emission rates of aldehydes from selected HVAC materials such as duct liners, duct sealing caulks and neoprene gaskets. In a laboratory study of ozone interactions with naturally-loaded filters from commercial buildings, Hyttinen et al (2003) observed the consumption of ozone in almost all of the filters. In their field experiments, the reduction in ozone concentrations varied from 8 to 26%; the highest ozone reduction was obtained in an HVAC unit with three stages of filtration**.** In a separate study, Halás and Bekő (2003) observed poor air quality downstream of filters exposed to ozone or air as compared to filters exposed to nitrogen. In their study, 90% of participants were dissatisfied with the air quality downstream of filters exposed to ozone, compared to 35% dissatisfied before the filters were exposed to ozone. They also showed a relatively high regeneration of the initial ozone removal efficiency after the samples were treated with clean air, nitrogen and 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 measured ozone removal efficiency, η, defined as the ratio of the ozone concentration difference across an HVAC filter to the ozone concentration upstream of the filter**,** for two residential filters. We then employ a well-mixed reactor model to determine the impact of HVAC filter removal

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on indoor ozone concentrations.

EXPERIMENTAL METHODOLOGY

Ozone removal efficiency, η, was used to describe ozone removal across an HVAC filter. Figure 1 depicts the experimental system used to determine η.

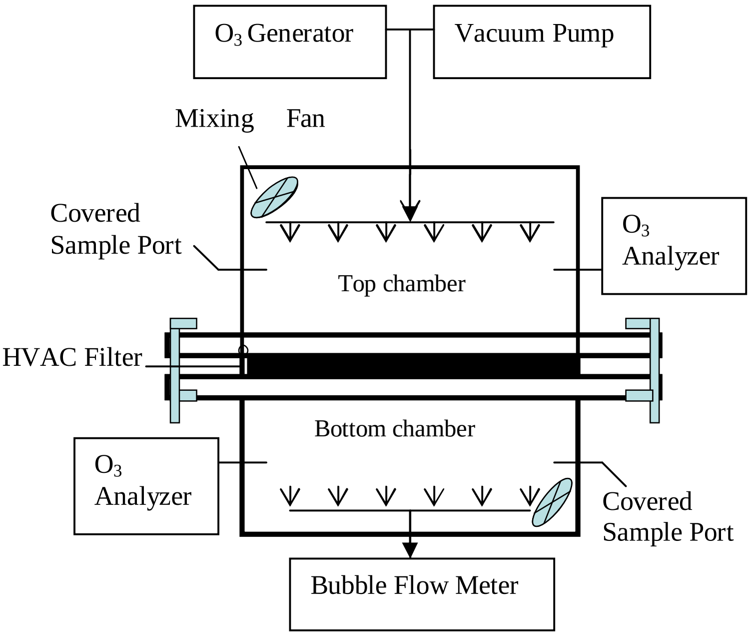

Figure 1. *Schematic of Experimental System*

A dual section electro-polished stainless steel chamber (28.3 L per section) was separated by the test filter. Small fans were used to mix the air in each section. All air passed through the HVAC filter was pre-filtered through a Polytetrafluoroethylene (PTFE) filter with pore size of 2.0 µm in order to keep particles from depositing on the sample filter. Thereafter, room air through a vacuum pump with fixed flow rate was mixed with ozone generated by an ozone generator (Prozone, Model PZ 6 Air). Mixed air was then conveyed through the chamber system (into the top chamber, through the filter, out of bottom chamber). The air flow rate through the filter was measured with a bubble flow meter (Sensidyne, Model Gilibrator 2) at the outlet of the bottom chamber, as shown in Figure 2. Two fiberglass filters were tested in this study. Both filters came from a residential HVAC system after use for one month (Filter #1) and three months (Filter #2). The temperature and relative humidity of each experiment were approximately 23 °C and 50%, respectively. Ozone concentrations upstream and downstream of the filter were continuously monitored and recorded by two calibrated UV ozone analyzers (2B Technologies, Model 202) with sampling intervals of 10 seconds. Each experiment lasted 4.5 hours. The ozone concentration upstream of Filter #1 increased while conducting the experiment and was approximately 700 ppb by the end of the experiment. The ozone concentration upstream for Filter #2 also increased during the experiment and was approximately 250 ppb by the end of the experiment.

RESULTS AND DISCUSSION

Some important properties of the tested HVAC filters are described in Table 1. Both filters are spun fiberglass filters that are commonly used in residential heating and cooling systems. When characterized by ASHRAE Standard 52.2 (1999), both filters have a minimum efficiency rating value (MERV) of less than 4. Both filters have a high porosity, as measured by submerging a known volume of bulk filter into a beaker of water and measuring the volume change.

Table 1. *Description of filters used in testing*

Filter #	Material	Thickness	Operation Duration	MERV Rating	Measured Porosity
1	continuous filament spun glass	2.75 cm	4 weeks	< 4	0.99
2	continuous filament spun glass	2.75 cm	12 weeks	< 4	0.99

Ozone Removal

The ozone concentration downstream of the filter was always less than the ozone concentration upstream for each experiment, which indicates that some ozone was removed when passing through the filter (Figures 2 and 3). For each filter, η (fractional ozone efficiency) varied from 0.1 to 0.24. These values are comparable to results reported by Hyttinen et al. (2003) for in-field measurements of ozone removal across HVAC filters in a commercial building. We observed that η decayed rapidly within the first 30 minutes of each experiment, presumably due to the consumption of reaction sites in the filter.

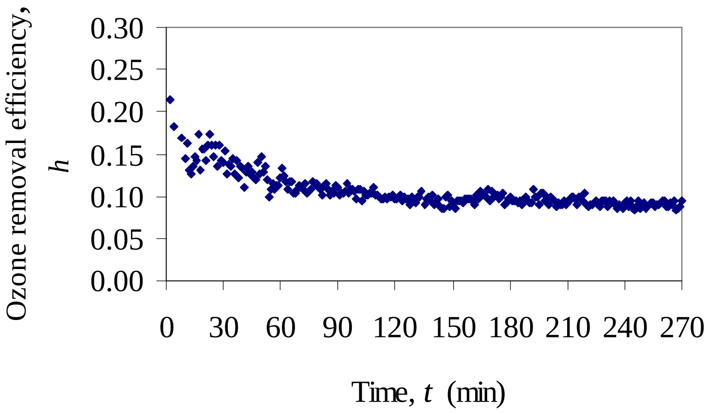

***Figure 2.** Ozone removal efficiency, η, as a function of time for Filter #1. The sample was initially exposed up to 700 ppb ozone for 4.5 hours.*

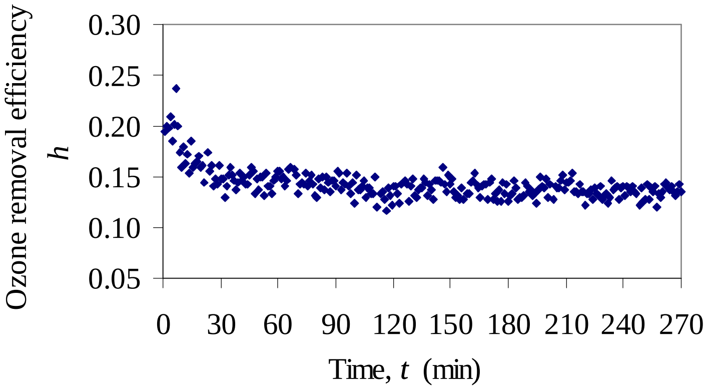

***Figure 3.** Ozone removal efficiency, η, as a function of time for Filter #2. The sample was initially exposed up to 250 ppb ozone for 4.5 hours.*

After this initial period of decay, η was almost constant during the rest of each experiment. These relatively constant values of η were found to be 0.1 for Filter #1 (Figure 2) and 0.14 for Filter #2 (Figure 3). Constant steady-state values of η may represent a balance between ozone consumption and diffusive replacement of reactive organic compounds from within particles. Inlet ozone concentrations for both experiments were much higher than typically observed for outdoor ambient ozone conditions. Also, in actual buildings particles will constantly deposit onto filters, and η would likely be greater than what we report here. Overall, it is uncertain how much the effects of continuous particle deposition, inlet ozone concentration, relative humidity, and air flow rate through a filter, would influence η. However, our results clearly indicate a non-zero removal efficiency of ozone across residential HVAC filters, and provide a starting point for screening calculations and more advanced experimental analysis.

Indoor Ozone Estimation with HVAC Filters

We performed a screening assessment to determine how the tested filters would affect indoor ozone concentration in a residence based on the steady-state ozone removal efficiency described above. A series of simplifying assumptions were made, including constant outdoor concentration, constant building air exchange rate, constant deposition loss rate, constant air flow rate through the HVAC system, no ozone source except for the infiltration of outdoor air, a well-mixed house volume, and steady-state conditions. The resulting mass balance for this system is shown in Equation 1

$$\frac{C_{in}}{C_{out}} = \frac{p\, l}{l + b + h\,\frac{Q_f}{V}} \tag{1}$$

where *p* is the penetration fraction for ozone through the building envelope (unitless), λ is the building air exchange rate (hr^{-1}), C_{out} and C_{in} are ozone concentration in outside air and inside air (ppb), respectively, β is the ozone deposition loss rate on indoor surfaces (hr^{-1}), Q_f is ventilation flow rate through the HVAC filter (m^3/hr), and *V* is the building air volume (m^3). We selected parameters based on the published literature. We assumed a value of 0.53 for ozone penetration, which is the mean value for an idealized fiberglass-insulated wall (Liu and Nazaroff 2001). Air exchange rate was varied from 0.2 or 2 hr^{-1} to cover a wide range of single-family residential dwellings, with a median value of 0.5 hr^{-1} (Murray and Burmaster 1995). The deposition loss rate, β, was taken to be 2.9 hr^{-1} or 5.4 hr^{-1}, depending on HVAC operation (Reiss ***et al.*** 1994). A typical house with a volume of 377 m^3 was selected by considering the typical home floor area from the 2001 American Housing Survey (2001) of 157 m^2 and an assumed ceiling height of 2.4 m. The flow through the air handler (Q_f) was determined by assuming a 3.5-ton air conditioner with a recommended HVAC flow of 2,040 m^3/hr. Experimental values of η of 0.1 for Filter #1 and 0.14 for Filter #2 were selected. We modeled four cases: (1) HVAC off, $Q_f = 0$ m^3/hr, $\beta = 2.9$ hr^{-1}; (2) Filter #1 only, $Q_f = 2{,}040$ m^3/hr, $\beta = 2.9$ hr^{-1} and $\eta = 0.1$; (3) Filter #2 only, $Q_f = 2{,}040$ m^3/hr, $\beta = 2.9$ hr^{-1} and $\eta = 0.14$; (4) Entire HVAC system, $\beta = 5.4$ hr^{-1} which includes all losses to a residential HVAC system, as tested by Reiss ***et al.*** (1994). Cases (2) and (3) assume that filters are the only HVAC component that participates in ozone reactions.

The ozone concentration ratios as a function of air exchange rate for all four cases are shown in Figure 4. Generally, indoor ozone reduction on either filter is predicted to be less than indoor ozone reduction by decreasing the air exchange rate. Over the range of air exchange rates considered, the ozone concentration ratio was reduced by 10 to 20 percentage points when comparing the HVAC off case to the two filter cases and 30 to 40 percentage points for the Entire HVAC system case. This analysis suggests that HVAC filters may not have a significant influence on indoor ozone concentrations, relative to reactions with indoor surfaces and other HVAC components. However, we ignored continuous particle deposition onto the filters and regeneration of filter reaction capacity due to diurnal variations in ozone concentration. We also tested only low-efficiency filters with very little particle cake. More efficient filters with a larger particle cake would likely lead to higher removal efficiencies.

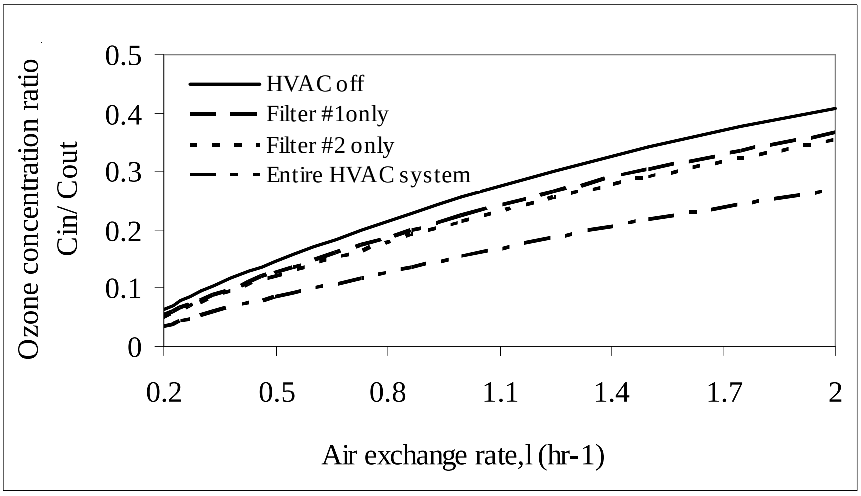

Figure 4*. Ozone concentration ratio as a function of air exchange rate for four different scenarios*

CONCLUSIONS

Two experiments involving ozone removal on HVAC filters were performed. Ozone concentration was observed to decrease across each filter. Ozone removal efficiency, η, dropped rapidly and then remained almost constant during the rest of each experiment, possibly due to regeneration of external reaction sites by internal diffusion of organic compounds in particles. In actual buildings, particles will constantly deposit onto filters, and η would likely be greater than what we report here. Based on our estimation, the tested filters wouldn't reduce indoor ozone levels as significantly as indoor surfaces with either HVAC systems on or off, or as significantly as decreasing the air exchange rate. Additionally, it is not yet clear whether the effects of different HVAC filters, continuous particle deposition, inlet ozone concentration, relative humidity, and air flow rate through the filter, can significantly affect ozone removal. Experiments are continuing to explore these factors.

ACKNOWLEDGEMENTS

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REFERENCES

ASHRAE. 1999. Standard 52.2 - 1999 Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Batterman S. and Burge H. 1995. “HVAC systems as emission sources affecting indoor air quality: a critical review,” International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research. 1 (1), 61-80.

Finke U., and Fitzner K. 1993. “Ventilation and air-conditioning systems-investigations to the odor and possibilities of cleaning,” Proceedings of the 6th International Conference on Indoor Air Quality and Climate-Indoor Air ’93, Helsinki: Indoor Air’93, Vol. 6, pp: 279-384.

Halás O. and Bekő G. 2003. “Ventilation filters as sources of pollution,” Master Thesis, Technical University of Denmark (Denmark), 140 pages.

Hyttinen M., Pasanen P., Salo J., Bjorkroth M., Vartiainen M. and Kalliokoski P. 2003. “Reactions of ozone on ventilation filters,” Indoor and Built Environment. 12(3), 151-158.

Liu DL. and Nazaroff WW. 2001. “Modeling pollutant penetration across building envelopes,” Atmospheric Environment. 35(26): 4451-4462.

Mendell MJ., Smith AH. 1990. “Consistent pattern of elevated symptoms in air-conditioned office buildings: a reanalysis of epidemiologic studies, ” American Journal of Public Health. 80, 1193-1199.

Morrsion GC., Nazaroff WW., Cano-Ruiz JA., Hodgson AT. and Modera MP. 1998. “Indoor air quality impacts of ventilation ducts: Ozone removal and emissions of volatile organic compounds,” Journal of Air and Waste Management Association. 48, 941-952.

Murray DM. and Burmaster DE. 1995.“Residential air exchange-rates in the united-states-empirical and estimated parameteric districutions by season and climatic region,” Risk Analysis. 15(4), 459-465.

Pejtersen J., Bluyssen P., Kondo H., Clausen G. and Fanger PO. 1989. “Air pollution sources in ventilation systems,” Proceedings of CLIMA 2000, Sarajevo: CLIMA 2000, Vol 3, pp: 139-144.

Reiss R., Ryan B. and Koutrakis P. 1994. “Modeling ozone deposition onto indoor residential surfaces”, Environmental Science & Technology, 28, 504-513.

U.S. Bureau of the Census. 2001. “American Housing Survey,” Washington, D.C.