Saving Energy and Improving IAQ through Application of Advanced Air Cleaning Technologies

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Introduction

In the future, we may be able use air cleaning systems and reduce rates of ventilation (i.e., reduce rates of outdoor air supply) to save energy, with indoor air quality (IAQ) remaining constant or even improved. The opportunity is greatest for commercial buildings because they usually have a narrower range of indoor pollutant sources than homes. This article describes the types of air cleaning systems that will be needed in commercial buildings.

Benefits and Costs of Outdoor Air Ventilation

Energy costs are incurred to heat, cool, and dehumidify ventilation air. In U.S. commercial buildings, an estimated 6.5% of site-consumed energy is used for conditioning mechanically-supplied ventilation, and approximately another 3% of site energy may be used to condition air from uncontrolled infiltration (Benne et al. 2009). The primary benefit of ventilation is its role in maintaining acceptable IAQ by exhausting polluted indoor air to outdoors and bringing in outdoor air free of indoor-generated pollutants. However, as detailed in **Table 1**, ventilation is marginally effectively in controlling our exposures to some types of indoor pollutants and ventilation is often unnecessary for control of combustion pollutants because many commercial buildings have no significant sources of combustion pollutants. Ventilation also brings outdoor-air pollutants into buildings. Commercial building ventilation is most helpful in reducing our exposures to indoor-generated volatile organic compounds (VOCs) such as formaldehyde from manufactured wood products and odorous gaseous bioeffuents. Ventilation can also help reduce our exposures to indoor-generated particles, although in commercial buildings we typically must filter the supplied outdoor and recirculated-indoor air to protect equipment and people from particles.

Criteria for Air Cleaning

Reducing ventilation rates to save energy, with no countermeasures, will increase indoor concentrations of indoor-generated VOCs and small particles by an amount that may degrade perceived air quality or pose health risks. If we reduce the ventilation rate by an amount ΔQ_v the pollutant removal rate R is diminished by the amount $\Delta Q_v \cdot C$, where C is the indoor air pollutant concentration. From a mass balance, to prevent IAQ from being degraded, we need to add an air cleaning system that provides the same or higher pollutant removal rate.

Table 1. IAQ impacts of ventilation (outdoor air supply) in commercial buildings.

Pollutant type	Exposures changes when ventilation rates are reduced	Explanation
Outdoor air pollutants	No change or decrease	Reduced ventilation sometime reduces our exposures to outdoor pollutants
Indoor generated VOCs	Increased	Ventilation flushes these pollutants out of buildings.
Indoor generated airborne particles	Small increase for indoor-generated particles and decrease for outdoor-air particles	Reduced ventilation will increase indoor concentrations but the impact of ventilation is small when indoor air is recirculated through efficient particle filters.
Indoor combustion –produced gaseous pollutants (e.g., CO, NO_x)	Increase, but generally not applicable	In most commercial buildings, there are no indoor sources or only very small sources. In buildings with combustion-based cooking, sources may be significant.
Radon	Increase, but generally not applicable	In most commercial buildings, radon levels are low
Semi-volatile organic compounds (e.g., plasticizers, flame retardants)	Not much change	These pollutants are mostly on indoor surfaces. Much of the airborne fraction is adsorbed on airborne particles. For some of these compounds, ingestion or dermal contact with surfaces are key routes of exposure.

For an air cleaner,

$$R = Q_{AC}\varepsilon\, C$$

where
Q_{AC} is the rate of air flow through the air cleaner, and
ε is the efficiency of pollutant removal by the air cleaner.

Thus, to maintain IAQ when the ventilation rate is decreased, the following must apply

$$Q_{AC}\varepsilon \geq \Delta Q_v$$

for the range of indoor-generated VOCs and particles that pose health risks or degrade perceived air quality. The product of Q_{AC} and ε is an effective flow rate sometimes called the clean air delivery rate. To save energy when we reduce ventilation in combination with air cleaning, the energy consumed per unit of clean air delivery for air cleaning must be less than the energy required per unit of outside air supply. Also, to be economically attractive the total cost per unit of clean air supply for air cleaning must be less than or equal to the total cost per unit air supply for ventilation. The criteria given above, assure that indoor concentrations of indoor-generated pollutants are not increased. Effective air cleaning will provide additional IAQ benefits by reducing indoor concentrations of VOCs and particles from outdoor air.

Availability of Air Cleaning Technologies meeting the Criteria

Assume that to save energy, we reduce the ventilation rate in a building by an amount ΔQ_v which is 50% of the normal minimum ventilation rate. Do we have the air cleaning technologies that meet our criteria for maintaining IAQ, saving energy, and being cost competitive? For particles, the answer is clearly yes. We already have effective, and low cost air cleaning technologies for particles, with fibrous filters being the most common. A filter with a MERV rating of 14 (EU rating of F7 or F8) is approximately 75% to 85% efficient in removing particles in the 0.35 to 0.64 micrometer range, thus, high efficiency particulate air filters are not necessary. There is only a modest incremental cost for filtration when we reduce ventilation and add particle filtration of recirculated indoor air. We avoid filtering a ventilation airflow of ΔQ_v, but to keep indoor airborne concentrations of small indoor-generated particles from increasing we must add filtered recirculated indoor air with a flow rate of

$$\frac{1}{\varepsilon_f}\Delta Q_v$$

where ε_f is the particle removal efficiency of the filter.

For our example MERV 14 filter with an ε_f of 0.75 for small particles, we must filter $1.3\Delta Q_v$ of recirculated indoor air, as opposed to filtering ΔQ_v of ventilation air for our base case. The costs of filtration are low. In U.S. buildings which typically filter a supply air stream with a flow rate of four times the total ventilation airflow (or eight times ΔQ_v in our example scenario), the total monthly filtration cost has been estimated at less than $2 per person per month for a MERV 14 filter (Fisk et al. 2002). Since particle filtration costs will scale approximately with the flow rate of air filtered, the incremental cost for filtering the extra $0.3\Delta Q_v$ of airflow is about $1 per person per year. From analyses of the results of modeling of the U.S. office building stock, we estimate that average energy cost just of heating ventilation air with natural gas is $3.1 per person per year, and the cost is higher in most other types of commercial buildings. Except in mild climates, filtration will be far more energy efficient and cost effective than ventilation for controlling concentrations of indoor-generated particles.

For VOCs, the answer is less clear, but the future is promising. The most mature VOC air cleaning technologies are granular activated carbon (GAC) for reversible adsorption of higher molecular weight VOCs and granular chemisorbents for removal, by permanent chemical reaction, of lower molecular weight easily-oxidized VOCs such as formaldehyde. The granular media are normally installed in trays placed in the supply airstream and disposed of when expended. While these granular media can be highly effective in removing a broad range of VOCs from air, they are costly, can impose a high airflow resistance, and have an uncertain lifetime in indoor air applications (Fisk 2007). Consequently, trays of granular media are not typically used in buildings unless there is a special need for VOC control. Another option is the use of fibrous particle filters that contain activated carbon grains within the fibrous media. Many major particle filter suppliers now offer such products. However, the amount of carbon in these filters may be too small to reliably adsorb VOCs for the duration of filter deployment, and the result of limited field testing of the VOC control capabilities of these filters is not encouraging (Fisk 2007).

We believe that emerging technologies show greater promise in meeting our criteria. One emerging technology that has received much attention is photocatalytic oxidation (PCO) air cleaning in which the air passes over a surface coated with a titanium dioxide catalyst irradiated with ultraviolet light. The system creates hydroxyl radicals and other reactive species that break down VOCs, ideally to carbon dioxide and water. A few issues must be resolved before PCO systems prove practical for our application. Many PCO systems fail to fully breakdown all VOCs to carbon dioxide and water vapor, and the products of incomplete VOC decomposition can pose health risks. Also, the catalyst can be deactivated or partially deactivated by common indoor air pollutants. There has been progress in addressing both of these issues, but the energy cost to operate the UV lamps and the initial and replacement cost of the UV lamps also remain barriers. Two emerging technologies that show promise are activated carbon fiber (ACF) systems, and metal-oxide catalysts that can destroy some pollutants at room temperature. ACF is available as a woven cloth-like media made of activated carbon. Like GAC, ACF adsorbs a broad range of VOCs. Unlike GAC, ACF can easily be regenerated in place. Periodically, e.g., each night, heated air can be passed through ACF cloth at a low flow rate for a short period to drive the previously adsorbed VOCs off the ACF media. These desorbed VOCs are then vented outdoors, making the ACF again ready to serve as an air cleaner. Advantages of ACF compared to GAC include a greatly smaller mass of carbon media, lower pressure drops, and potentially longer life and much lower costs. We have studied ACF system performance with mixtures of VOCs, with VOC properties ranging from those of formaldehyde (molecular weight 30, boiling point –21°C) to undecane (molecular weight 156, boiling point 196°C). The research results as shown in **Figure 1** suggest that an ACF system coupled with a 50% reduction in ventilation rate will substantially improve IAQ, and that the energy required is only about 10% of the energy typically required in the U.S. for ventilation (Sidheswaran et al. 2011a). A metal-oxide catalyst showing great promise in breaking down formaldehyde and other easily oxidizable compounds is manganese oxide (MnO_x). Various deployment options for this catalyst are being evaluated including inside wallboards (Sekine and Nishamura 2001) and on surfaces placed in airstreams. In our research, we are applying this catalyst to the fibrous media of typical particle filters and removing formaldehyde, at room temperature, with 80% efficiency (Sidheswaran et al. 2011b). The material costs are low and the catalyst synthesis is not complex. With these new air cleaning technologies, or others, the potential is high for ventilation energy savings with IAQ maintained unchanged or improved.

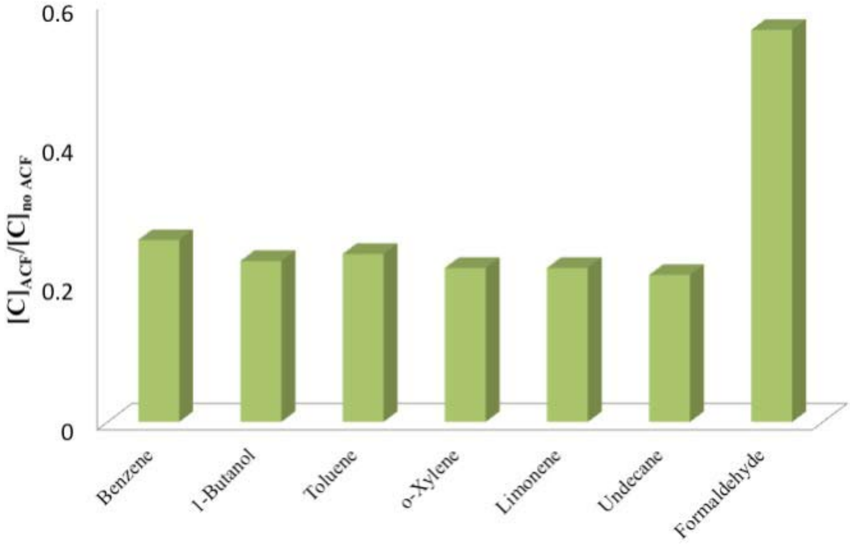

Figure 1. Ratio of Concentration of Common Pollutants during Air-Cleaning with 50% Reduction in Ventilation to Concentration of Common Pollutants with no Air-Cleaning. Air exchange rate was assumed to be 1/h (Sidheswaran et al., 2011a)

Acknowledgments

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. Department of Energy under contract DE-AC02-05CH11231. We thank Junseok Park and Spencer Dutton for reviewing a draft.

References

Benne, K., B. Griffith, N. Long, P. Torcellini, D. Crawley and T. Logee (2009). Assessment of the energy impacts of outside air in the commercial sector, NREL/TP-550-41955. Golden, CO, National Renewable Energy Laboratory.

Fisk, W. J. (2007). Can sorbent-based gas phase air cleaning for VOCs substitute for ventilation in commercial buildings? IAQ 2007, Healthy and Sustainable Buildings. Atlanta, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.

Fisk, W. J., D. Faulkner, J. Palonen and O. Seppanen (2002). Performance and costs of particle air filtration technologies. Indoor Air 12(4), 223-34.

IOM (2000). Clearing the air: asthma and indoor air exposures, Institute of Medicine, National Academy of Sciences. Washington, D.C., National Academy Press.

Sekine, Y. and A. Nishamura (2001). Removal of formaldehyde from indoor air by passive type air cleaning materials. Atmospheric Environment 35, 2001-2007.

Sidheswaran, M., H. Destaillats, D. P. Sullivan and W. J. Fisk (2011a). Energy efficient indoor VOC air cleaning with activated carbon fiber (ACF) filters. Building and Environment (submitted).

Sidheswaran, M., H. Destaillats, D. P. Sullivan, J. Larsen and W. J. Fisk (2011b). Quantitative room temperature mineralization of airborne formaldehyde using manganese oxide catalysts. Applied Catalysis B- Environment (submitted).