TEMPERATURE AND AIRFLOW INFLUENCES INDOOR AIR BIOFILTRATION

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ABSTRACT
Biofiltration is an alternative to ventilation for maintaining indoor air quality. Our biofilters were comprised of complex communities of plants which provides many ecological niches for microbial colonization while having strong aesthetic appeal. This study focused on the effects of temperature and airflow on biofiltration of volatile organic compounds (VOCs). Indoor biofilters typically function very well at ambient temperatures. However, some poorly degraded VOCs have low solubilities. Reduced biofilter temperatures may improve degradation by increasing contaminant solubility, however this may be offset by reduced microbiological activity. Another advantage of subambient temperatures is a reduction in humidity loading on the indoor air stream. Test biofilters were run at temperatures of 17 and 27 °C. Ambient methylethylketone (MEK) and benzene concentrations ranged from 10 to 80 ppbv. Benzene removal was greater at 27 °C suggesting microbially limiting conditions while MEK removal was higher at 17 °C inferring substrate-limiting conditions.

INDEX TERMS
Biofiltration, VOC degradation, Temperature, Humidity

INTRODUCTION
Indoor air quality is traditionally maintained through ventilation. The displacement of 'stale' indoor air with 'fresh' outdoor air lowers the concentrations of contaminants that tend to accumulate in the indoor air stream. However, the cost associated with conditioning the fresh air in terms of temperature and humidity has led to buildings becoming increasingly sealed. This is especially true in climates of extreme heat and cold, where conditioning the incoming outdoor air is a substantial component of building operating costs. The consequence of 'air tight' buildings is that contaminants such as volatile organic compounds (VOCs) can accumulate to levels that may affect occupant comfort and health. The VOCs associated with poor quality indoor air range widely in physical properties (including solubility) and biological activity. Single VOC concentrations are typically less than 10^{-6} to 10^{-4} g m^{-3} and mixed VOC concentrations less than to 10^{-3} g m^{-3} (Godish, 1991).

Biofiltration may be an alternative to ventilation for maintaining indoor air quality. In general, a biofilter is composed of a population of microorganisms bound to a porous substrate an aqueous layer called a biofilm. As air passes though the biofilter, contaminants are transferred into the biofilm where they are subject to microbial attack. Contaminants are metabolized as a source of energy and are converted into their benign constituents, namely CO_2 and H_2O (Bibeau, Kiared, Leroux et al., 1997). Conventional, compost-based biofilters are a proven, energy-efficient technology for treating industrial waste gas streams. However

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conventional biofilters are designed to treat 10^5 to 10^8 times higher VOC concentrations than are typical of an indoor space (Arcangeli and Arvin, 1995; Devinny, Deshusses and Webster, 1999).

In indoor biofiltration, the air stream is recirculated through a biologically complex, plant-based ecosystem. Plant roots, mosses and other organic material provide the primary substrate for microbial colonization. The biofilter is kept in a moisture-saturated environment, via a recirculating water supply, to maintain plant health and biofilm activity. The integration of higher plants borrows from phytoremediation technology where plants improve biodegradation of contaminated soil and water. Green plants may facilitate VOC removal and can enhance microbial populations through symbioses and root exudates (Siciliano and Germida 1998). The complexity of these systems allows a variety of degraders to occupy numerous ecological niches. Microbial population diversity optimizes the opportunity for the destruction of the wide variety of contaminants typical of any occupied indoor space (Pritchard, Mueller, Lantz et al,. 1995).

Past research has shown that ecologically complex biofilters have a positive effect of indoor air quality in terms of VOC concentrations (Darlington, Dixon and Pilger, 1998; Darlington, Dat and Dixon, 2001) while having no impact on indoor spore loads or bioaerosols (Darlington, Chan, Malloch, et al. 2000; Mallany, Darlington and Dixon, 2000). Biofiltration has potential as a strategy for maintaining indoor air quality. Further studies are required to develop engineering specifications and optimize this technology in the indoor setting.

Indoor biofilters function well at ambient temperatures. However, hydrophobic VOCs such as BTEX (benzene, toluene, ethylbenzene and xylene) have reduced removal efficiencies compared to more soluble VOCs such as ketones. Phase transfer into the aqueous biofilm may be the rate-governing step for less soluble VOCs (Hodge and Devinny, 1997). This is especially true in an indoor biofilter, where the ambient concentrations are so low. In this case, reduced biofilm temperatures may improve the degradation of these compounds by increasing their solubility in water. This advantage may be offset, however, by reduced microbiological activity at lower temperatures (Darlington, Dat and Dixon, 2001). This study tested the relative roles of temperature and airflow rate on the biofiltration of benzene and methylethylketone (MEK).

Another advantage of running the biofilter at cooler (ie. subambient) temperatures may be a reduction in humidity loading of the indoor air stream. Temperature and relative humidity (RH) are the two most important factors of air quality that affect occupant comfort. ASHRAE institutional standards are 20-25 °C for temperature and 30-60 % RH (ASHRAE, 1989). In passing ambient air through a moist biofilter, there is the opportunity to raise the effluent RH to 100% (thus lowering the temperature to dewpoint). The effluent may require dehumidification and re-heating to bring it back to within standard levels. By running the biofilter at sub-ambient temperatures, it may be possible to lower the cost of effluent air treatment.

METHODS

Six individual, lab-scale biofilters were operated in a partially sealed, 65 m^3 laboratory at the University of Guelph, Ontario, Canada. The biofilters were comprised of various moss species and coconut fiber with a surface area of 0.075 m^2 and an average depth of 1.6 ± 0.2 cm. The biofilters were watered for 5 s every 5 min by an overhead misters. Each biofilter

had a 2 l water reservoir that supplied the misting system and collected any runoff. There was no liquid water was loss from the biofilters

A SRI model 310 gas chromatograph (GC) coupled to a custom gas sampling multiplexer was used to monitor VOC concentrations in the ambient air and the effluent stream of each biofilter (Figure 1). The GC operated in autosampler mode, measuring each biofilter effluent stream approximately once and the ambient air 5 times per hour. This provided real-time analysis of VOC removal. Biodegradation was measured as the ratio of effluent concentration to a calculated, time-weighted ambient concentration (removal efficiency). This removal ratio may then be converted to mass loading and elimination rates ($g_{(VOC)}\ m^2_{(biofilter)}\ h^{-1}$) with the inclusion of airflow and biofilter surface area.

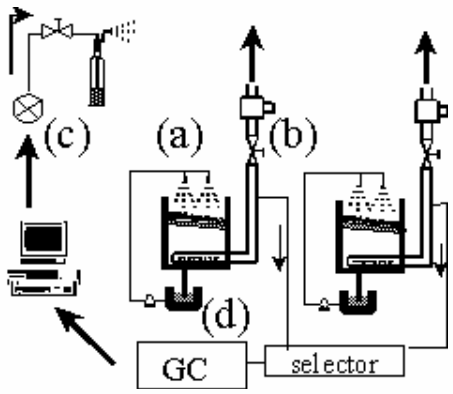

Figure 1. Schematic of biofilter apparatus (two biofilters shown). a) misting, b) effluent fan, c) VOC emitter, d) biofilter sump

The GC was also used as the sensor in a feedback loop controlling the ambient VOC concentrations. Briefly, a peripheral emitter system would monitor the results of each ambient air measurement. It would then increase the ambient VOC concentrations if required to desired levels by passing metered volumes of air through impingers containing pure solvents. VOC-saturated air would then be emitted into the room's air stream via the HVAC. Ambient VOC concentrations followed a diurnal profile ranging from 10 ppbv to 80 ppbv with an average concentration of 48 and 44 ppbv for MEK and benzene respectively. This synthetic diurnal pattern more closely reflects the fluctuations seen in indoor air streams than a steady state.

Biofilter temperature was varied by controlling the room air temperature via the HVAC. The room was set to 2 different temperatures: 27 and 17 °C and the biofilters were operated with 3 different flow rates: 0.05, 0.10 and 0.20 m s^{-1}. The flow rate of each biofilter was randomized daily in a Latin square design so each biofilter operated at each flow rate 3 times at each temperature setting. Airflow was measured with a hand-held anemometer (Model 8346, TSI Inc., St. Paul, MN). Ambient and effluent temperature of each biofilter was measured with thermocouples and recorded 4 times per hour with a Campbell CR-7 datalogger (Edmonton, AB).

RESULTS AND DISCUSSION

The biofilters were actively removing MEK and benzene prior to the beginning of the experiment. They were commissioned several weeks before and had acclimated to MEK and benzene during that time. It should be noted that the biofilters were not inoculated with VOC-degrading microbes. Hence, VOC-degraders were either indigenous populations in the moss or they were present in the ambient air. The acclimation period (data not presented) was typical for indoor biofilters exposed to ketones and BTEX as described by Darlington and Dixon (2002). Rapid MEK acclimation was indicative of large, healthy populations of indigenous MEK degraders already present in the biofilters. A 5-day lag for benzene acclimation suggested there were lower initial populations of benzene degraders. It may also take longer for benzene degraders to react to a new carbon source and assimilate the necessary metabolic enzymes (Alexander, 1985).

MEK removal was higher than benzene regardless of temperature and airflow (Figure 2.). It should also be noted that benzene removal was highest at 27 °C while MEK removal was highest at 17 °C. This suggests that benzene removal was limited by microbiological activity while MEK removal was substrate-limited. This evidence was supported by the rapid MEK and slower benzene acclimation at startup. Henry's Law coefficients (atm m^3 mol^{-1}) for MEK and benzene are $2.39*10^{-4}$ and $4.17*10^{-3}$ at17 °C and $1.31*10^{-4}$ and $6.02*10^{-3}$ at 27 °C respectively (Ashworth, Howe, Mullins et al., 1988). Hence, MEK is roughly an order of magnitude more soluble than benzene. In addition, benzene solubility roughly increases by a third while MEK solubility doubles at 17 °C versus 27 °C. However, the increased biofilm concentrations of benzene appear to have been offset by reduced metabolic activity of benzene degraders at 17 °C. Sorial, Smith, Suidan et al. (1997) and Lu, Lin and Chu (1999) observed this trend in conventional BTEX-degrading biofilters, where optimum removal efficiency was at temperatures above 30 °C. Figure 2. also indicates that removal efficiency increased with decreasing airflow. This is generally true for conventional biofilters where the effluent is exhausted to the atmosphere (Devinny, Deshusses and Webster, 1999). However, where the effluent stream is recycled, single-pass removal efficiency is less significant than absolute contaminant elimination. When the removal data were converted to mass loading and elimination rates (Figure 3.), the biofilters removed the largest quantity of contaminants at the highest loading rates (ie. highest airflow). The biofilters were capable of eliminating 43 and 18 mg m^{-2} h^{-1} of MEK and benzene respectively at the highest air flow and 27 °C. Benzene elimination was roughly doubled at the higher temperature while MEK elimination was relatively unaffected. This would suggest that indoor biofilters will be most efficient at higher airflows and elevated temperatures. However, this has to be balanced with the increased costs of dehumidifying the effluent stream.

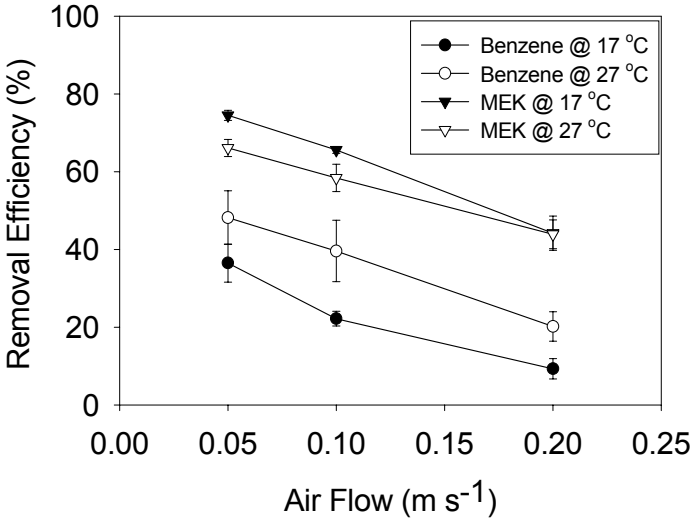

Figure 2. Effect of airflow and temperature on biofiltration of MEK and benzene

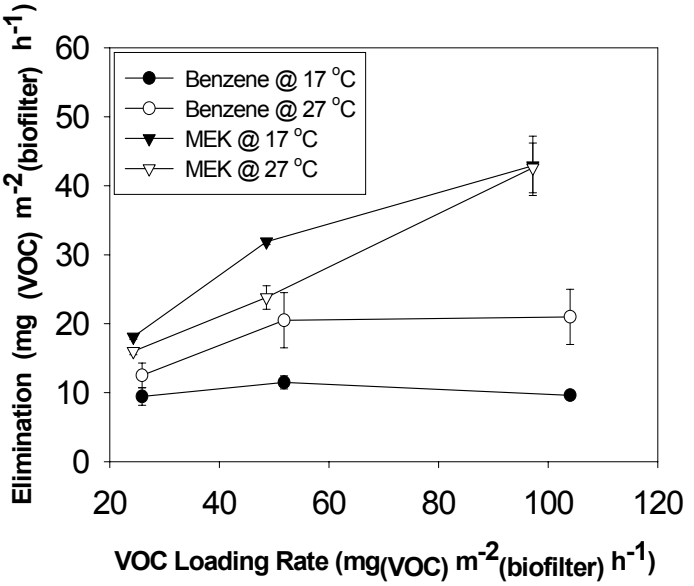

Figure 3. Mass VOC loading and elimination rates at 17 and 27 °C

There was a substantially larger cooling effect of the effluent air at the higher airflow rates (Figure 4.). This was an evaporative cooling effect where, as water evaporated, it removed

heat energy from the air. There was also a reduced cooling effect at airflows below 0.2 m s^{-1}. This was evidence of breakthrough at lower airflows where the boundary layer within the pores of the biofilter medium increased with reduced flow so that a portion of the air passed through the biofilter without humidification. This psychometric phenomenon was described in Woodward and Sheehy (1983) where the degree of cooling rises logarithmically with increasing airflow. When the empirical data was fit to this model, insignificant increases in cooling would occur at airflows beyond 0.2 m s^{-1} (ie. the effluent air would be saturated). Hence, above 0.2 m s^{-1}, humidity loading on the indoor space would be approximately proportional to airflow (at set temperature and RH).

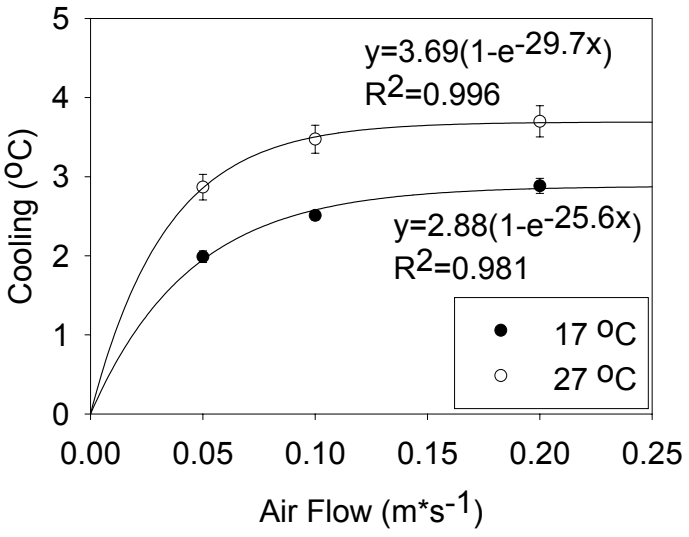

Figure 4. Influence of airflow on effluent cooling

CONCLUSION AND IMPLICATIONS

Ecologically complex biofilters can have a positive impact on indoor air quality in terms of contaminant removal. Further testing is required, but this study indicates that the airflow should be as fast as possible and at elevated temperatures. Airflow will ultimately be limited by the practicalities of fan sizing while biofilter temperature can easily be elevated by heating the recirculating water supply. These benefits may however, be offset by the additional cost of dehumidifying the effluent stream.

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