MULTIZONE MODELING OF THREE RESIDENTIAL INDOOR AIR QUALITY CONTROL OPTIONS

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ABSTRACT

The impact of central forced-air heating and cooling system modifications on the levels of selected pollutants in single-family houses was evaluated by simulating pollutant concentrations due to a variety of sources in eight houses with typical HVAC systems. Simulations were performed with a multizone airflow and pollutant transport model and were repeated with the systems modified to include an electrostatic particulate filter, a heat recovery ventilator, and an outdoor air intake damper. The system modifications reduced the pollutant levels in the houses for some cases; however, the results also demonstrated potential limitations in both the simulation method and the performance of the devices.

INTRODUCTION

Central forced-air heating and cooling systems can have a significant impact on indoor air quality in residential buildings because these systems circulate large volumes of air, spreading pollutants generated in one room to the rest of the house. They also can act as a source of indoor air pollution, for example, due to damp or dirty ductwork and filters. However, modifications to forced-air systems have the potential to improve indoor air quality (IAQ) through the addition of air cleaners or devices to introduce outdoor air into the house.

Evaluating the effectiveness of such modifications could require extensive field testing. Computer modeling can provide insight without the time and effort required to perform field tests. Such a modeling effort requires a whole building approach that accounts for the multizone nature of airflow and pollutant transport in residential buildings and considers all relevant factors - air leakage paths in the building envelope and interior walls, wind pressure profile on the building envelope, pollutant sources, HVAC system airflows, filter efficiencies, pollutant sinks, pollutant decay or deposition, and ambient weather and pollutant concentrations. Many residential IAQ studies have employed simplified approaches to studying buildings and their HVAC systems. For example, some studies have ignored the multizone nature of the problem (Hamlin and Cooper 1992, Novosel et al. 1988) and others have not rigorously modeled building airflow (Owen et al. 1992, Sparks et al. 1989). A few studies have employed a whole building modeling approach (Li 1993, Yuill et al. 1991).

In this effort, a multizone airflow and pollutant transport model was used to conduct a preliminary assessment of the potential for using central forced-air heating and cooling systems to control IAQ in residential buildings. This effort was not intended to determine definitively whether the IAQ control options modeled are reliable and cost-effective. Rather, the objective was to provide insight into the potential of these options to mitigate residential IAQ problems, the pollutant sources they are most likely to impact, and their potential limitations. Another important objective was to identify key issues related to the use of multizone airflow and pollutant transport models to study IAQ control in residential buildings.

METHODOLOGY

The program CONTAM93 (Walton 1994) was used to simulate the pollutant levels due to a variety of sources in eight buildings with typical HVAC systems under different weather conditions. The HVAC systems were then modified with three IAQ control technologies including an electrostatic particulate filter, a heat recovery ventilator, and an outdoor air intake damper. Altogether, 96 simulations were performed to evaluate the performance of these modifications for controlling the following sources: constant-emission volatile organic compound (VOC) sources, intermittent-emission VOC sources, combustion pollutant sources, and elevated outdoor pollution.

CONTAM93

CONTAM93 (Walton 1994) is a multizone airflow and pollutant transport model employing a graphic interface for data input and display. Multizone models take a macroscopic view of airflow and IAQ by calculating average pollutant concentrations in the different zones of a building as contaminants are transported through the building and its HVAC system. The multizone approach is implemented by assembling a network of elements describing the airflow paths between the zones of a building. The

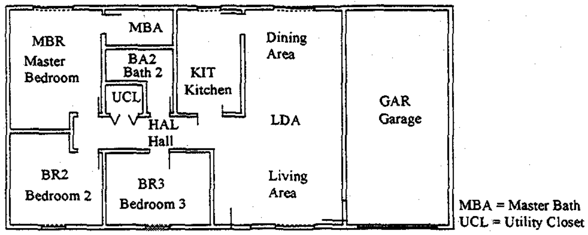

Figure 1 - Ranch house floorplan and zones

network nodes represent the zones that contain pollutant sources and sinks and are modeled at a uniform temperature and pollutant concentration.

Building Factors

The study included eight building models - a ranch and a two-story house, located in two sites (Miami and Minneapolis), with typical and low levels of air leakage. All rooms of the houses, even closets, were modeled as separate zones. The ranch and two-story house floorplans and zone labels (in all capitals) are shown in Figures 1 and 2, respectively. The Minneapolis houses have basements (zone label BMT) that are not shown in the figures. Simulations were performed under three sets of weather conditions which were chosen by selecting a hot, mild, and cold day for each location from Weather Year for Energy Calculation (WYEC) data (Crow 1983). Each simulation was performed for a one-day cycle repeated until peak concentrations converged to a specified tolerance.

The air leakage of the house envelopes and interior partitions was modeled by including elements for leakage paths typically found in residential buildings.

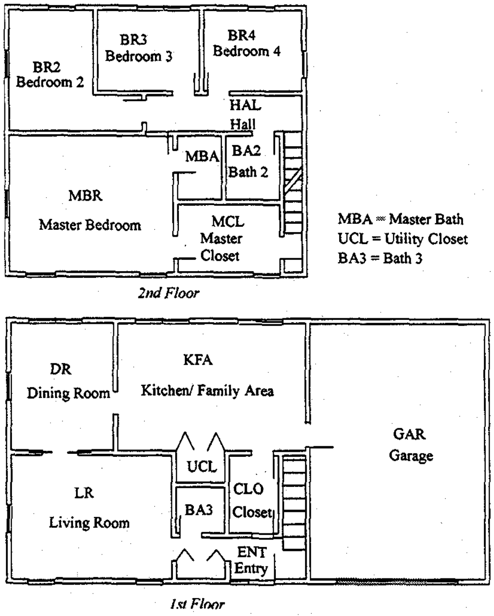

Figure 2 - Two-story house floorplan and zones

Table 1 shows the leakage paths between the zones of the Miami ranch house. Table 2 lists the values specified for those leakage paths for both the typical and tight cases. The Table 2 leakage areas are for a reference pressure difference of 4 Pa and a discharge coefficient of 1.0 and are based on values listed in Table 23-3 of ASHRAE (1993) unless otherwise noted. All doors connecting interior zones other than closets were modeled as open. The same leakage values were used for the other houses, although the paths connecting the zones differed.

Airflow rates through openings in a building's envelope also depend on the static pressure distribution created by the wind on the building's exterior surfaces. The relationship between wind and surface pressures is characterized by wind pressure coefficients that depend on the wind direction, the building shape, the position on the building surface, and the presence of shielding near the building. The wind pressure coefficients for the building walls were based on Equation 23-8 of ASHRAE (1993). The coefficient for the flat garage roof was based on Figure 14-6 of ASHRAE (1993). Wind shielding effects can be important but were not considered.

Table 1 - Air leakage paths for Miami ranch house

	MBR	BR2	BR3	MBA	BA2	UCL	KIT	LDA	HAL	GAR	ATC
BR2	INTW OUTL										
BR3		INTW OUTL									
MBA	INTD INTW										
BA2	INTW OUTL			INTW OUTL							
UCL	INTW				INTW						
KIT				INTW OUTL	INTW OUTL						
LDA			INTW OUTL				INTW INTD OUTL				
HAL	INTD INTW	INTD INTW	INTD INTW OUTL		INTD INTW	CLD INTW	INTD INTW OUTL	HAD			
GAR								EXTD EXW OUTL			
ATC	CEIL CPEN	CEIL CPEN	CEIL CPEN	CEIL CPEN PIP	CEIL CPEN PIP	CEIL CPEN	CEIL CPEN	CEIL CPEN CPEN	CEIL ATD		
AMB	WIN EXW OUTL	WIN EXW OUTL	WIN EXW OUTL	EXV EXW OUTL	EXV		WIN EXV EXW OUTL	SGD EXTD WIN EXW OUTL		GAD GARF EXW	VNT
	MBR	BR2	BR3	MBA	BA2	UCL	KIT	LDA	HAL	GAR	ATC

Table 2 - Air leakage values

Name	Description	Typical	Tight
ATD	Attic door	30 cm2/ea	18 cm2/ea
CEIL	Ceiling [Based on general ceiling]	1.8 cm2/m2	0.79 cm2/m2
CLD	Closet door (closed) [Based on interior door]	0.9 cm2/m	0.25 cm2/m
	Closet door frame [Based on general door frame]	25 cm2/ea	12 cm2/ea
CPEN	HVAC ceiling penetration [Based on kitchen vent with damper closed]	5 cm2/ea	1 cm2/ea
EXTD	Exterior door [Single]	21 cm2/ea	12 cm2/ea
	Exterior door frame [Wood]	1.7 cm2/m2	0.3 cm2/m2
EXV	Bathroom exhaust vent	20 cm2/ea	10 cm2/ea
	Kitchen exhaust vent	40 cm2/ea	5 cm2/ea
EXW	Ceiling-wall joint and wall-wall joint	1.5 m2/m	0.5 m2/m
	Floor-wall joint	4 cm2/m	0.8 cm2/m
GAD	Garage door [Based on general door (2 m x 4 m)]	0.45 cm2/m	0.31 cm2/m
	Garage door frame [Wood]	1.7 cm2/m2	0.3 cm2/m2
GARF	Garage roof [Based on general ceiling]	1.8 cm2/m2	0.79 cm2/m2
HAD	Hall doorway	2.4 m2/ea	2.4 m2/ea
INTD	Interior door (closed) [Based on Table 4.2 of Klote and Milke 1992]	140 cm2/ea	75 cm2/ea
	Interior door (open)	2.1 m2/ea	2.1 m2/ea
INTW	Interior wall [Based on gypsum board on stud wall (Shaw et al. 1991)]	2.0 cm2/m2	2.0 cm2/m2
OUTL	Electric outlet	2.5 cm2/ea	0.5 cm2/ea
PIP	Piping penetrations	6 cm2/ea	2 cm2/ea
SGD	Sliding glass door	22 cm2/ea	3 cm2/ea
VNT	Attic vent [Based on Table 21-1 of ASHRAE 1993]	1 cm2 / 300 cm2	1 cm2 / 300 cm2
WIN	Double hung window	2.5 cm2/m	0.65 cm2/m
	Window framing [Wood]	1.7 cm2/m2	0.3 cm2/m2

Fan pressurization tests in the houses were simulated with CONTAM93 by adjusting the flow through a constant flow element in the door until internal/external pressure differences of 4 and 50 Pa were achieved. The results of the fan pressurization simulations (see Table 3) indicate that the tight houses are about 66% tighter than the typical houses. Emmerich and Persily (1994a) describes additional airflow simulations performed on the Miami ranch house including the evaluation of building air change rates under a variety of conditions and simulated tracer gas decay tests.

Table 3 - Fan pressurization simulation results

House	ach50 (hr-1)	Leakage area (cm2)
Typical Miami ranch	13.2	680
Tight Miami ranch	4.1	220
Typical Minneapolis ranch	6.6	720
Tight Minneapolis ranch	2.2	230
Typical Miami 2 story	12.9	1,120
Tight Miami 2 story	4.6	390
Typical Minneapolis 2 story	8.8	1,170
Tight Minneapolis 2 story	3.1	410

HVAC System Factors

The buildings were modeled with typical residential central forced-air heating and cooling systems. The systems were selected based on cooling and heating load calculations performed using the method in the ASHRAE Handbook of Fundamentals (ASHRAE 1993). The air distribution systems were designed based on guidelines from the National Association of Home Builders (Yingling 1981). System operation schedules were determined by calculating the fractional on-time required to meet the cooling or heating load. Detailed descriptions of the systems including load calculations, heating and cooling equipment, and distribution system drawings are included in Emmerich and Persily (1994b).

Duct leakage can have an important impact on IAQ by affecting pressure relationships between zones. It was modeled by including an additional supply or return point and reducing the other supply and return flows. Based on the results of field measurements in 160 Florida houses (Cummings et al. 1991), a duct leak equal to 10% of the total system flow was included. In the Minneapolis houses, a return leak was located in the basement. Only a supply leak was included in the Miami ranch house attic because the system has a central, unducted return. For the Miami two-story house, no leaks were included because all ducts are internal.

The baseline HVAC systems included standard furnace filters with constant efficiencies of 5% for fine particles (diameter less than 2.5 μm) and 90% for coarse particles (diameter greater than 2.5 μm). These efficiency values are based on assumed arrestance for these filters of about 90% and a review of manufacturers' test data.

Pollutant Factors

The pollutants of interest for this study were nitrogen dioxide (NO_2), carbon monoxide (CO), particulates, and volatile organic compounds (VOCs). A literature review of reports quantifying residential sources of these pollutants was performed (Emmerich and Persily 1994b). The pollutant sources included several VOC burst (short duration) sources, a constant VOC area source, and combustion sources of CO, NO_2, and fine particles. Table 4 lists information on these sources including the zones in which they are located, source strengths, and time-patterns.

Table 4 - Pollutant sources

Source	Pollutant	Zone(s)	Source strength	Schedule
Burst (medium)	TVOCs	Several	300 mg/h	9 - 9:30 am 7 - 7:30 p.m.
Burst (high)	TVOCs	GAR and BMT	1100 mg/h	9 - 10 am 7 - 8 p.m.
Flooring material	TVOCs	All but GAR, ATC	7.0 mg/h m2	constant
Oven	CO	KIT (ranch house), KFA (two-story house)	1900 mg/h	7 - 7:30 am 6 - 7 p.m.
Oven	NO2	KIT (ranch house), KFA (two-story house)	160 mg/h	7 - 7:30 am 6 - 7 p.m.
Oven	Fine particles	KIT (ranch house), KFA (two-story house)	0.2 mg/h	7 - 7:30 am 6 - 7 p.m.
Heater	CO	GAR and BMT	1000 mg/h	7 - 10 am (GAR) 7 - 9 p.m. (BMT)
Heater	NO2	GAR and BMT	250 mg/h	7 - 10 am (GAR) 7 - 9 p.m. (BMT)
Heater	Fine particles	GAR and BMT	2 mg/h	7 - 10 am (GAR) 7 - 9 p.m. (BMT)

Typical outdoor pollutant concentrations were used to account for pollution entering the dwelling from outside and provide background levels for the indoor sources. The CO and NO_2 concentrations were chosen based on a review of US EPA air quality documents (EPA 1991, EPA 1993a, EPA 1993b). They were selected to have a diurnal pattern with morning and afternoon peaks. The CO concentration varied from 1 to 3 ppm, and the NO_2 concentration varied from 20 to 40 ppb. A constant fine particle concentration of 13 $\mu g/m^3$ was used based on Sinclair et al. (1990). A constant TVOC concentration of 100 $\mu g/m^3$ was used based on Shields and Fleischer (1993).

Elevated outdoor concentrations of CO, NO_2, and coarse particles were also simulated to evaluate the impact of the IAQ control technologies on pollutants brought into residences from outside. These elevated pollutant concentrations were selected based on a review of US EPA air quality documents (EPA 1991, EPA 1993a, EPA 1993b). The elevated CO and NO_2 concentrations had a diurnal pattern with morning and afternoon peaks. The CO concentration varied from 4 to 12 ppm, and the NO_2 concentration varied from 200 to 400 ppb. The coarse particle concentration was constant at a level of 75 $\mu g/m^3$.

Reversible sink effects for the VOCs were modeled with sink elements based on a boundary layer diffusion controlled (BLDC) model with a linear adsorption isotherm described by Axley (1990). The model parameters include the film mass transfer coefficient, the adsorbent mass, and the isotherm partition coefficient. Little data is available for these parameters which depend on airflow rates, gas diffusion properties, and adsorbent material. The values used for the parameters were 35 $\mu m/s$ for the film mass transfer coefficient, 0.5 g-air/g-sorbent for the partition coefficient, and 3 kg per m^2 of zone interior surface area for the adsorbent mass.

NO_2 decay and particle deposition were modeled as single-reactant first order reactions with a single, constant value in all zones. NO_2 decay depends strongly on the materials present in a house (e.g., floor and wall coverings, furnishings, etc.) and a wide range of measured values have been reported. The kinetic rate coefficient used for NO_2 decay was 0.87 h^{-1} and is based on the average of measurements in a contemporary research house (Leslie et al. 1988).

Particle deposition depends on the size and type of particles, particle concentration, airflow conditions, and surfaces available for deposition. The fine particle deposition rate used was 0.08 h^{-1} and is based on combustion products from a wood-burning stove in a test house (Traynor et al. 1987). The coarse particle deposition rate used was 1.5 h^{-1} and is based on the lower value reported for 4 μm particles in a test room (Byrne et al. 1993).

IAQ Control Technologies

The IAQ control technologies considered for the study were limited to commercially available equipment that can be used with conventional forced-air systems. IAQ controls and ventilation systems that operate independently of a forced-air system, such as whole-house exhaust ventilation systems, were not considered. The three control technologies included were electrostatic particulate filtration, heat recovery ventilation, and an outdoor air intake damper on the forced-air system return. This report discusses only the important modeling details. More information including duct drawings, cost estimates, and thermal loads may be found in Emmerich and Persily (1995).

The electrostatic particulate filter (EPF) selected for the study has a filter efficiency of 30% for fine particles (emitted by the combustion sources in these simulations) and 95% for coarse particles (associated with the elevated outdoor air concentrations). The

EPF was modeled by replacing the standard furnace filters in the baseline HVAC systems. The filter efficiency was modeled as constant over time with no impact on airflow through the system.

The heat recovery ventilator (HRV) draws air from the return side of the forced-air system and replaces it with outdoor air drawn through the heat exchanger. The actual outdoor airflow rate during operation was selected to provide an air change rate of 0.35 ach through the HRV. The HRV was modeled by setting the outdoor airflow rate for each HVAC system to the appropriate fraction of the total system supply airflow rate. Thus, the desired amount of outdoor air will be supplied whenever the HVAC system is operating. Other control options (such as constant operation or demand control) were not studied. A standard furnace filter was included in the outdoor air intake path of the HRV. The HRV employs a defrost cycle that periodically closes the outdoor air damper in cold weather. The defrost cycle was not modeled.

The outdoor air intake damper (OAID) draws outdoor air into the return side of the forced-air system. The OAID was modeled similarly to the HRV. The HVAC system was modified to include a constant fraction of outdoor air to provide an air change rate of 0.35 ach through the system during operation. A standard furnace filter was included in the outdoor air intake path. The primary difference between the OAID and the HRV is that the outdoor air intake damper does not include an exhaust duct. Therefore, the outdoor airflow will tend to pressurize the house. This effect was modeled by reducing the HVAC return flows from the house by an amount equal to the outdoor air supplied to the system.

RESULTS

Figure 3 shows a sample of the transient simulation results for a burst VOC source for a baseline HVAC system. This figure shows the TVOC concentrations in the living and dining area (LDA), kitchen (KIT), and master bedroom (MBR) zones resulting from a burst source in the LDA for the tight Miami ranch house in cold weather. As expected, two concentration peaks, corresponding to the source schedule in Table 4, are seen in zone LDA. The adjacent zone KIT also shows two peaks, however, the KIT concentration peaks are significantly lower than the LDA peaks and occur from one to two hours after the LDA peaks. The peaks are not clearly distinguishable for the MBR that is located on the opposite end of the house as the LDA. (Note: Figure 3 shows the TVOC concentration rising at 9 a.m. when the source is scheduled to begin emitting. This occurred for all cases because the program interpreted the scheduled sources to begin one calculation time step (five minutes) before the scheduled time.)

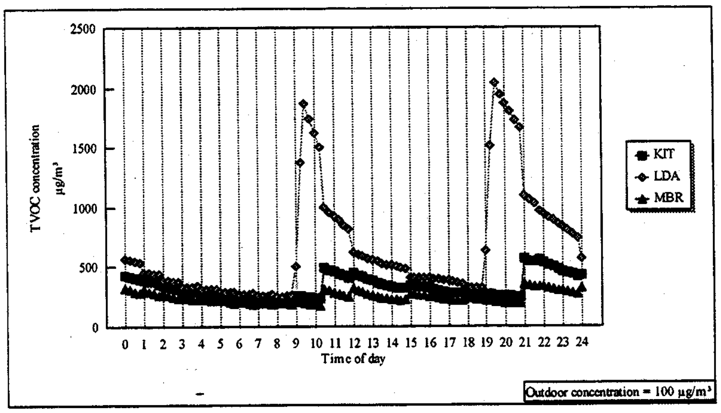

Figure 3 - TVOC concentration in tight Miami ranch house due to LDA burst source (baseline cold weather case)

Figure 4 shows the impact of the HRV on the living-space average TVOC concentrations for the above case. The living-space average includes the KIT, LDA, MBR, BR2, and BR3 zones. The HRV reduced the peak TVOC concentration by only 2.5% but reduced the 24-hour average living-space concentration by 14%.

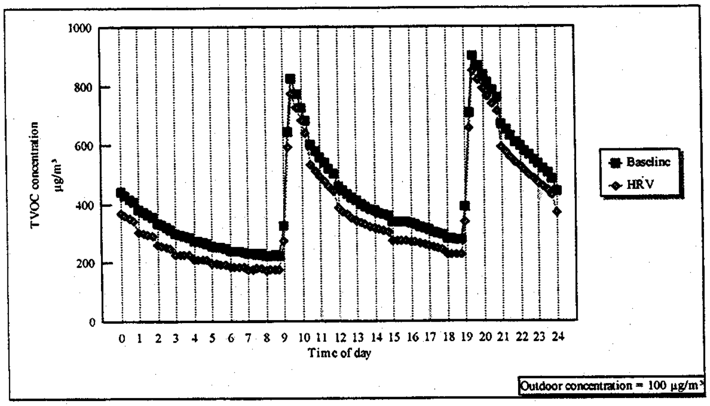

Figure 4 - Transient living-space TVOC concentration in tight Miami ranch house due to LDA burst source (cold weather case)

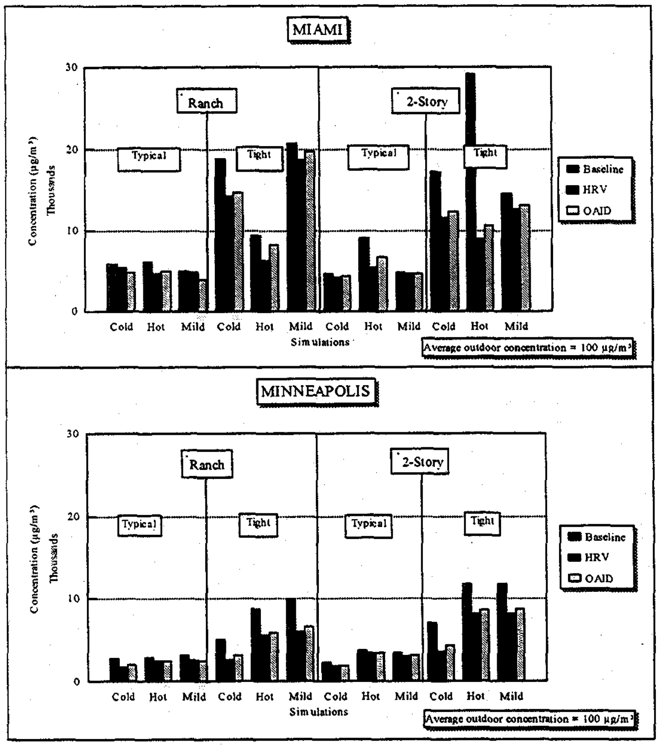

Figure 5 - 24-hour, living-space average TVOC concentrations due to floor source

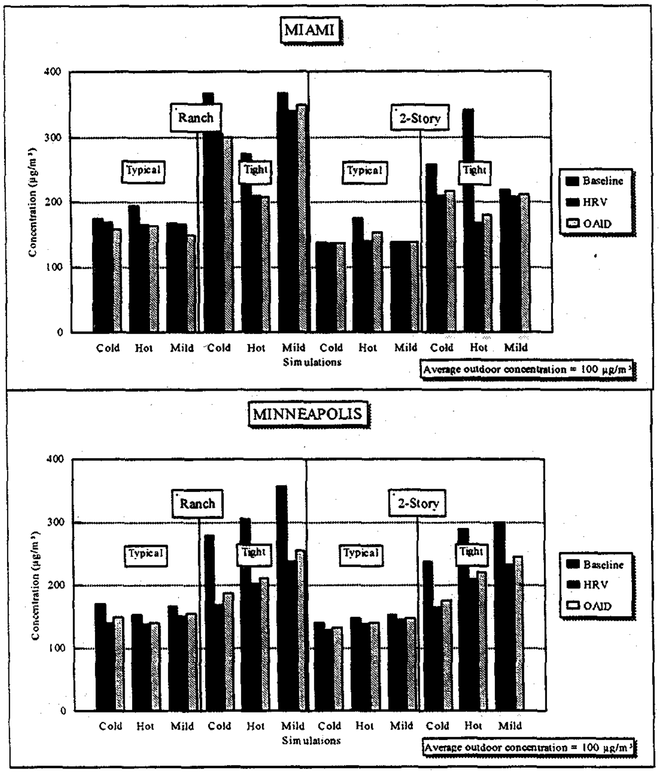

Figure 6 - Average of 24-hour, living space average TVOC concentrations due to burst sources

Figure 5 shows the 24-hour, living-space TVOC concentrations due to the floor source for all baseline, HRV, and OAID cases. The HRV and OAID reduced the baseline 24-hour average TVOC concentrations by averages of 26% and 21%, respectively. The impact of the house envelope tightness is evident as the concentrations in the tight houses are substantially higher than in the corresponding typical houses. The additional outdoor air brought into the houses by the IAQ retrofits reduced the baseline 24-hour average TVOC concentrations in the tight houses by a larger relative amount than in the typical houses (35% versus 16% for the HRV and 29% versus 14% for the OAID). However, the concentrations in the tight houses with the modifications were still higher than the baseline concentrations in the typical houses.

The results for the floor source also indicate that the modifications have a limited impact during weather conditions which require low system run-time to meet the heating and cooling loads. For example, the city and weather combination resulting in the lowest system run-time is Miami mild weather with an average run-time of 7%. On average, the Miami mild weather cases also show the smallest percent reductions in TVOC concentrations, 7.5% for the HRV and 13% for the OAID. The conditions (small stack and wind effect driving forces) causing low system run-time generally also correspond to low infiltration rates and high pollutant concentrations. Therefore, days with high concentrations due to low infiltration could receive the least help from the HRV or OAID due to low system run-time. For example, the tight Miami ranch house in mild weather has the second highest baseline 24-hour average TVOC concentration (20,700 µg/m³) but, after modest reductions due to the HRV and OAID, it ends up having the highest TVOC concentrations for the modified cases with concentrations of 16,800 µg/m³ and 18,600 µg/m³, respectively. The effectiveness of the central forced-air modifications could also be limited if the cooling and heating equipment is oversized . Although it was not explored in this study, oversized equipment would further reduce the HVAC

Table 5 - Average percent reductions of 24-hour, living-space average concentrations due to IAQ control retrofits

IAQ Control	Floor - VOC	Burst - VOC	Oven - CO	Oven- NO2	Oven- Particles	Heater - CO	Heater- NO2	Heater- Particles	OA- CO	OA- NO2	OA- Particles
EPF	NA	NA	NA	NA	30	NA	NA	31	NA	NA	1.4
HRV	26	14	10	-2.3	-14	8.1	-7.5	-9.9	0.1	-37	-3.9
OAID	21	13	7.9	-3.2	-10	7.1	-3	-7.6	0.2	-30	9.3

system run-time. The system run-time limitation could be overcome through other control options for these devices (such as constant operation, demand control, or scheduled operation) or through other approaches to residential ventilation.

Figure 6 summarizes the 24-hour, living-space average TVOC concentrations due to the VOC burst sources for the baseline, HRV, and OAID cases. This figure uses the average of the concentrations due to all eight VOC burst sources located in various zones to represent the average impact of the IAQ controls on localized sources in different rooms of the house. The HRV and OAID reduced the baseline TVOC concentrations by averages of 14% and 13%, respectively. These results support the observations made above that the impact in the tight houses is larger than in the typical houses (with reductions of 22% versus 6.8% for the HRV and 20% versus 7% for the OAID) and that the smallest reduction occurred in the Miami mild weather cases (3.3% for the HRV and 5.0% for the OAID).

Table 5 summarizes the effectiveness of each retrofit at reducing 24-hour living-space average concentrations for all sources. Overall, the EPF had a small impact on the already low coarse particle concentrations with an average reduction of only 1.4%. This small impact is due to the small change in coarse particle filtration efficiency from 90% to 95%. Table 5 indicates that the EPF was more effective at reducing the fine particle concentrations with reductions of 30% and 31% for the oven and heater sources, respectively.

The HRV and OAID did not reduce indoor pollutant concentrations for all cases. Table 5 shows that the HRV and OAID both significantly increased the concentrations of NO_2 for the elevated outdoor NO_2 case. This increase occurs because the NO_2 inside the house is entirely due to the outdoor levels and decay reactions cause lower levels inside than outside. Because particles also are removed from the indoor air, the HRV increases coarse particle concentrations due to the elevated outdoor levels. However, on average, the OAID reduced the coarse particle concentrations. This result may be due to the OAID pressurizing the indoor space, which reduces unfiltered outdoor air entering through envelope leaks. On average, the HRV and OAID also increased the NO_2 and fine particle concentrations caused by the heater and oven because the indoor source strength and duration and the deposition/decay removal rates resulted in low indoor concentrations relative to the outdoor concentrations. Therefore, increased outdoor air intake increases the indoor concentrations. However, whether an increase or decrease occurred for an individual case depended on several factors including the building air change rate, the indoor source strength, the outdoor pollutant concentration, decay/deposition rates, and the timing of the source, system operation, and outdoor concentration peaks.

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CONCLUSIONS

The process of performing whole building airflow and pollutant transport simulations of the pollutant concentrations in residential buildings was described in detail. Simulation results indicate that, in certain cases, modifications to typical residential forced-air heating and cooling systems reduce indoor pollutant concentrations. The IAQ controls reduced the pollutant concentrations more in the tight houses than in the typical ones. However, the heat recovery ventilator and outdoor air intake damper *increased* pollutant concentrations for certain situations. Whether an increase or decrease occurred for an individual case depended on factors with a considerable range and/or uncertainty of input values such as the indoor source strength, the outdoor pollutant concentration, and pollutant decay/deposition rates. System run-time under mild weather conditions was identified as a potential limitation of forced-air system modifications. However, this limitation could be overcome through other control options for these devices or through other approaches to residential ventilation.

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