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Effectiveness of a Heat Recovery Ventilator, an Outdoor Air Intake Damper and an Electrostatic Particulate Filter at Controlling Indoor Air Quality in Residential Buildings

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Synopsis

A preliminary study of the potential for using central forced-air heating and cooling system modifications to control indoor air quality (IAQ) in residential buildings was performed. The main objective was to provide insight into the potential of three IAQ control options to mitigate residential IAQ problems, the pollutant sources the controls are most likely to impact, and the potential limitations of the controls. Another important objective was to identify key issues related to the use of multizone models to study residential IAQ and to identify areas for follow-up work. The multizone airflow and pollutant transport program CONTAM93 (1) was used to simulate pollutant concentrations due to a variety of sources in eight houses with typical HVAC systems under different weather conditions. The simulations were repeated after modifying the systems with three IAQ control technologies - an electrostatic particulate filter, a heat recovery ventilator (HRV), and an outdoor air intake damper (OAID) on the forced-air system return. Although the system modifications reduced pollutant concentrations in the houses for some cases, the HRV and OAID increased pollutant concentrations in certain situations involving a combination of weak indoor sources, high outdoor concentrations, and indoor pollutant removal mechanisms. Also, limited system run-time during mild weather was identified as a limitation of IAQ controls that operate in conjunction with forced-air systems. Recommendations for future research include: simulation of other buildings, pollutants, and IAQ control technologies; model validation; sensitivity analysis; and development of a database of important model inputs.

1. Introduction

Central forced-air heating and cooling systems can have a significant impact on IAQ in residential buildings because they 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 dirty ductwork. However, forced-air system modifications have the potential to improve 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 coefficients, 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 (2,3) and others have not rigorously modeled building airflow (4,5). A few studies have employed a whole building modeling approach (6,7).

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. The objective of this effort was to provide insight into the use of state-of-the-art IAQ models to evaluate such modifications, the potential of these modifications to mitigate residential IAQ problems, the pollutant sources they are most likely to impact, and their potential limitations. This study was not intended to determine definitively whether the IAQ control options studied are reliable and cost-effective.

Another important objective was to identify key issues in the use of multizone airflow and pollutant transport models to study IAQ in residential buildings.

2. Modeling Method and Parameters

The program CONTAM93 (1) was used to simulate the pollutant levels due to a variety of sources in eight houses with typical HVAC systems. CONTAM93 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 network nodes represent the zones containing pollutant sources and sinks and are modeled at a uniform temperature and pollutant concentration.

Simulations were performed for a hot, mild, and cold day for each location using Weather Year for Energy Calculation (WYEC) data (8). Each simulation consisted of a one-day cycle repeated until peak concentrations converged to a specified tolerance. 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 impact of these controls on pollutants from the following sources: a constant-emission volatile organic compound (VOC) source, intermittent-emission (burst) VOC sources, combustion pollutant sources, and elevated outdoor pollution.

2.1 Buildings

The CONTAM93 description of buildings includes the building zones, characteristics of leakage paths connecting zones, and the wind pressure coefficients of leaks through the building envelope. The buildings were described in an earlier paper (9), and in greater detail in reference 10. The study included eight buildings - a ranch and a two-story house, located in two sites (Miami and Minneapolis), with typical and low levels of air leakage. 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 BMT) not shown in the figures.

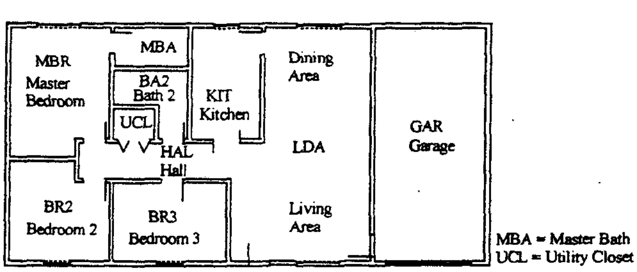


Figure 1 - Ranch House Floorplan and Zones

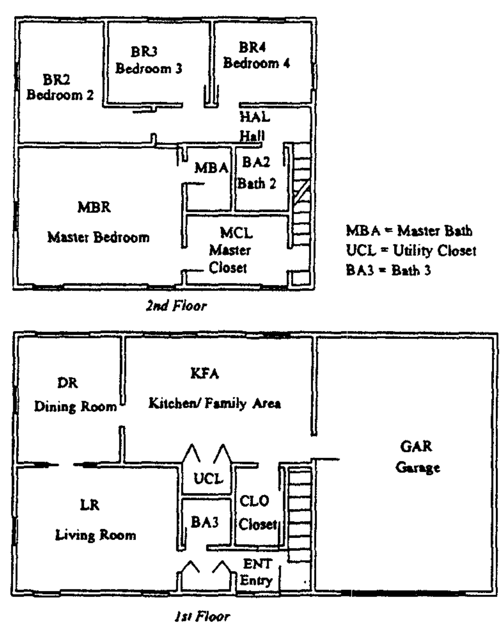


Figure 2 - Two-story House Floorplan and Zones

The air leakage of the house envelopes and interior partitions was modeled by including elements for leakage paths typically found in residential buildings. Most of the leakage values were based on Table 23-3 of ASHRAE (11). All doors connecting interior zones other than closets were modeled as open. The wind pressure coefficients for the building walls and the flat garage roof were based on Equation 23-8 and Figure 14-6 of ASHRAE (11), respectively. Wind shielding effects can be important but were not considered.

2.2 HVAC Systems

The CONTAM93 description of HVAC systems includes the total system airflow, supply and return locations and flow rates, outdoor air supply flow rates, and operating schedules. The buildings were modeled with typical residential central forced-air heating and cooling systems with modest duct leakage and no outdoor air intake. System operation schedules were determined by calculating the fractional on-time required to meet the cooling or heating load. The baseline 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). The systems are described in greater detail in references 9 and 12.

2.4 Pollutant Factors

The pollutants of interest for this study were nitrogen dioxide (NO_2), carbon monoxide (CO), particulates, and volatile organic compounds (VOC). Based on a literature review of reports quantifying residential sources of these pollutants (12), the pollutant sources included eight VOC burst (short duration) sources, a constant VOC area source, and combustion sources of CO, NO_2, and fine particles. The concentrations due to each source of the same pollutant were calculated separately. Table 1 lists information on these sources including the zones in which they are located, source strengths, and time-patterns.

Table 1 - 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 selected to have a diurnal pattern with morning and afternoon peaks, and varied from 1 to 3 ppm for CO and 20 to 40 ppb for NO_2 based on a review of US EPA air quality documents (13-15). A constant fine particle concentration of 13 $\mu g/m^3$ is based on reference 16, and a constant TVOC concentration of 100 $\mu g/m^3$ is based on reference 17.

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 also based on EPA air quality documents (13-15). The elevated CO and NO_2 concentrations also had a diurnal pattern with morning and afternoon peaks, and varied from 4 to 12 ppm for CO, and 200 to 400 ppb for NO_2. The coarse particle concentration was constant at a level of 75 $\mu g/m^3$.

Reversible sink effects for the VOC were modeled with sink elements based on a boundary layer diffusion controlled (BLDC) model with a linear adsorption isotherm (18). 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 μm/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), and a wide range of measured values have been reported. The kinetic rate coefficient used for NO_2 decay was 0.87 h^{-1} based on the average of measurements in a contemporary research house (19). 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} based on particles from a wood-burning stove in a test house (20). The coarse particle deposition rate used was 1.5 h^{-1} based on the lower value reported for 4 μm particles in a test room (21).

2.5 IAQ Control Technologies

The IAQ control technologies considered for the study were limited to commercially available equipment that can be used with typical forced-air systems. Ventilation systems and IAQ controls that operate independently of a forced-air system (e.g. whole-house exhaust ventilation systems) were not considered. The three control technologies 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 is in reference 10.

The electrostatic particulate filter (EPF) 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 pollution). 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 h^{-1} through the HRV. The HRV was modeled by setting the outdoor airflow rate for each HVAC system to the appropriate fraction of the system supply airflow rate. Thus, outdoor air will be supplied by the HRV whenever the HVAC system is operating. Other control options were not studied (e.g. demand control). A standard furnace filter was included in the intake path of the HRV.

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 by modifying the HVAC system 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 also included. The primary difference between the OAID and the HRV is that the OAID does not include an exhaust duct. Thus, the OAID 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.

3. Results

3.1 *Outdoor Air Change Rates*

The impact of the HRV and OAID may be evaluated by comparing the resulting air change rates in the houses with those required by ASHRAE Standard 62 (21). Standard 62 requires a minimum outdoor air change rate of 0.35 h^{-1} or, if greater, 7.5 L/s (15 cfm) per person with an assumption of 2 people for the first bedroom and 1 person for each additional bedroom. Therefore, the minimum outdoor air change rates are 0.41 h^{-1} for the Miami ranch house, and 0.35 h^{-1} for all other houses.

Figure 3 shows the 24-hour average air change rates for the houses for all baseline, HRV, and OAID cases. The Minneapolis air change rates were calculated including the volume of the basement. The baseline average air change rate is below the ASHRAE minimum air change rate for all tight houses under all weather conditions. While the HRV and OAID do increase the building air change rates for all cases, the benefit is limited by the HVAC system run-time. With the HRV, the tight Miami houses meet the ASHRAE minimum air change rate on the hot day but still fall short on the cold and mild days. The tight Minneapolis houses meet the requirement on the cold day but still fall short on the mild and hot days.

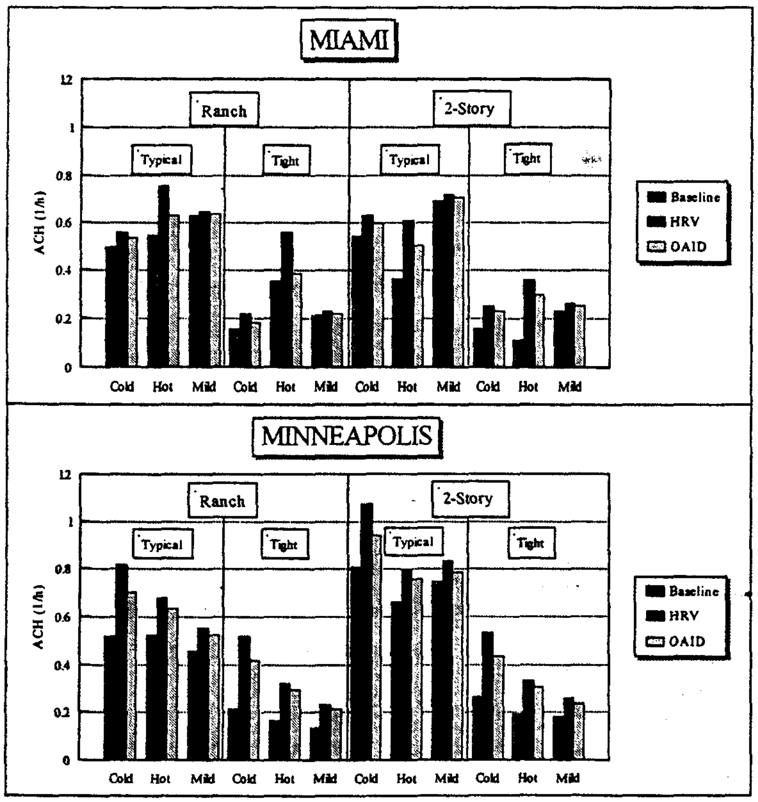


Figure 3 - 24-hour Average Building Air Change Rates

Figure 3 also demonstrates an important difference between the HRV and the OAID. In all cases, the OAID increases the building air change rate by a smaller amount than the HRV. Because the OAID does not have an exhaust path, the air entering the house through the OAID pressurizes the building and reduces infiltration through envelope leaks. This reduction of envelope infiltration partially offsets the increase in building air change rate due to the outdoor air entering through the OAID, causing a smaller overall increase than the HRV.

The Miami results also show one impact of duct leakage.

The baseline ranch and 2-story house results are quite close for the cold and mild days. However, for the hot day, the baseline air change rate in the 2-story house is substantially smaller than in the ranch house. The difference between the two is the a 10% supply duct leak in the attic of the ranch house (no duct leakage was included for the two-story house because the ducts are all within the conditioned space). Since the system runs most of the time on the hot day, duct leakage has a significant impact on the air change rate of the ranch house. The contribution of duct leakage to the air change rate of the Miami ranch house is less noticeable on the cold and mild days as the system operates much less.

3.2 *Sample Transient Results*

Figure 4 shows the impact of the HRV and OAID on the living-space average TVOC concentrations due to the LDA burst source for the tight Miami ranch house, cold day case. The living-space average includes the kitchen, living room, dining room, and all bedroom zones. When the HVAC system comes on, the concentration drops suddenly due to the additional outdoor air brought in through the HRV and the OAID. When the system is off, the concentration decreases at a lower rate due to infiltration. Both the HRV and OAID had small impacts on the concentration peaks (reductions of 2.5% and 3.4%, respectively) but more substantial impacts on the 24-hour average concentrations (reductions of 14% and 17%, respectively). The small reductions in peak concentrations indicate an inability of the modest increase in ventilation rate to mitigate concentration spikes due to a short-term source. [Note: Figure 4 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 time step (five minutes) before the scheduled time.]

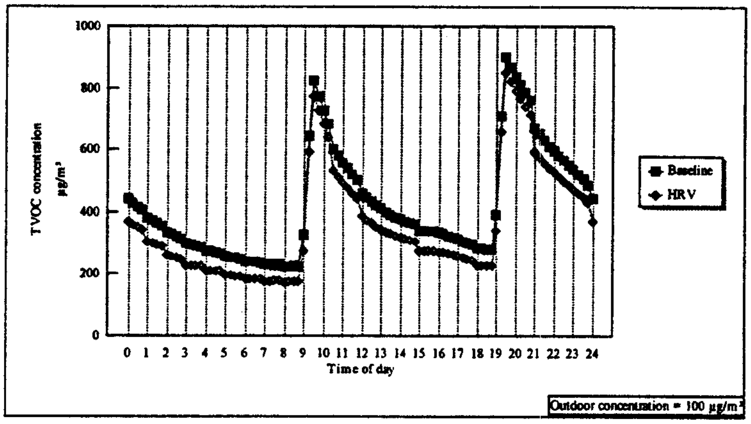


Figure 4 - Transient Living-space TVOC Concentration Cue to LDA Burst Source (Tight Miami Ranch House on Cold Day)

Figure 5 shows the living-space average concentrations due to the floor TVOC source for the tight Miami ranch house in cold weather. Since the floor source is constant, the concentration changes are due primarily to changes in the building air change rate with

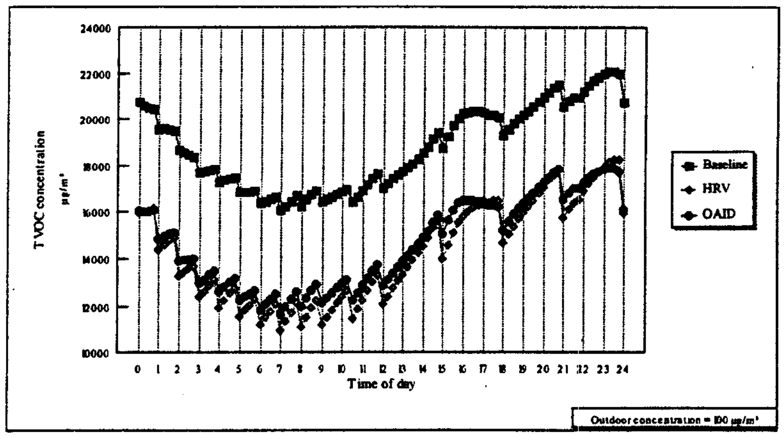
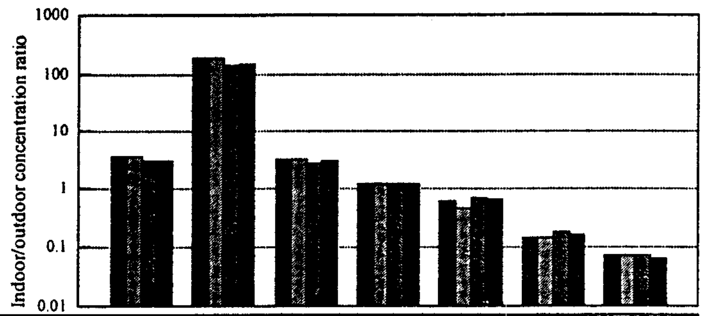


Figure 5 - Transient Living-space TVOC Concentration Due to Floor Source (Tight Miami Ranch House on Cold Day)

the outdoor conditions and with HVAC system operation. In general, the TVOC concentration gradually increases when the system is off and then drops sharply when the system turns on due to the higher air change rate. Overall, the concentrations are higher during the latter part of the day because the system operates less frequently and the infiltration driving forces are lower, both resulting in a lower air change rate. As explained earlier, system operation increases the outdoor air change rate in this house due to the supply duct leak in the attic. The HRV and the OAID reduced both peak (19% and 18%, respectively) and average TVOC concentrations (22% and 24%, respectively) for the floor source by a greater amount than for the burst source. The IAQ controls have a greater impact on the peak concentration for the floor source than for the burst sources because the floor-source peak is due to a gradual build-up of pollutant through the day rather than a short-term event.

3.3 *Impact of IAQ Controls on Average Pollutant Concentrations*

Figure 6 shows the ratio of the 24-hour, living-space average concentrations to the 24-hour average outdoor concentration for the baseline, EPF, HRV, and OAID cases in the tight, Miami ranch house on the cold day. The indoor/outdoor ratios are shown on a log scale as they range over five orders of magnitude depending on the source. The VOC burst source results shown use the average of the concentrations due to all eight burst sources to represent the average impact of the IAQ controls on localized sources in different rooms of the house. The variation in the indoor/outdoor ratio among the sources is due to the relative values of the source strength, indoor decay mechanisms and outdoor pollutant concentrations. The controls themselves have much less impact on these ratios, but the effects can still be seen.



Source	Burst-VOC	Floor-VOC	Oven-CO	Oven-NO2	Oven-fine	OA-NO2	OA-coarse
Baseline	3.7E+00	1.9E+02	3.2E+00	1.2E+00	6.2E-01	1.4E-01	6.9E-02
EPF	3.7E+00	1.9E+02	3.2E+00	1.2E+00	4.4E-01	1.4E-01	6.8E-02
HRV	3.0E+00	1.4E+02	2.7E+00	1.2E+00	6.8E-01	1.8E-01	7.1E-02
OAID	3.0E+00	1.5E+02	3.0E+00	1.2E+00	6.5E-01	1.6E-01	6.1E-02

Figure 6 - Indoor/outdoor Ratios of Average Concentrations Due to Various Sources (Tight Miami Ranch House on Cold Day)

The average impact of the IAQ controls for all pollutant sources are shown in Figure 7 as percent reductions in baseline concentrations. In general, both the HRV and OAID reduced the concentrations due to indoor sources of the pollutants without non-ventilation removal processes (CO and VOC) and increased, or had little impact, on the concentrations of pollutants with decay/deposition and filtration removal processes (NO_2 and particles). The HRV and OAID had the greatest reduction for the constant, distributed source (Floor-VOC), which was also the source resulting in the largest indoor/outdoor concentration ratio. In general, the HRV and OAID increase NO_2 and particle concentrations because, as shown in Figure 6, the baseline average indoor concentration is below the average outdoor concentration. Therefore, the additional outdoor air brought in by these controls increases the indoor concentration. Figure 7 shows that this trend was true on average. However, whether

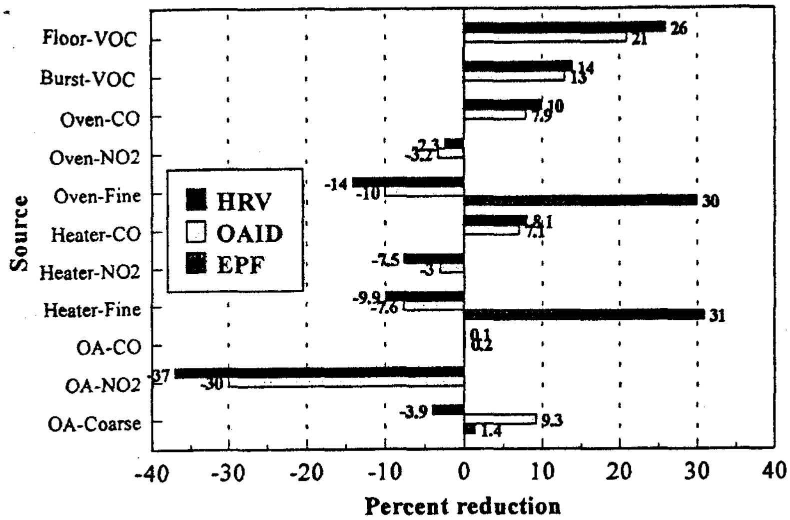


Figure 7 - Average Reductions in Living-space Average Concentrations

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 peaks.

The impact of the OAID was nearly always similar to but slightly smaller than the impact of the HRV because, as shown in Figure 3, it increases the average building air change rate by a smaller amount than the HRV. As discussed previously, this smaller increase in building air change rates is due to the pressurization effect of the OAID. However, the HRV and OAID did not always have similar impacts, as seen in the case of coarse particle concentrations due to elevated outdoor air pollution. For this pollutant, the OAID reduced the baseline concentration by an average of 9.3% while the HRV increased the baseline concentration by an average of 3.9%. This impact is believed to be due to the pressurization effect of the OAID. Both devices include a standard furnace filter with filtration efficiency of 90% for coarse particles in the intake path. However, no penetration factor was included for infiltration air and, therefore, the filtered air entering through the OAID and HRV has a lower particle concentration than the unfiltered air entering through the envelope. Since the operation of the OAID results in less infiltration than the baseline and HRV cases, it reduces the indoor coarse particle concentration.

In general, 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%. Figure 7 shows 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. It should be noted that, as indicated by the indoor/outdoor ratios, the conditions simulated provided only a modest challenge to the EPF.

3.4 Factors Influencing Impact of IAQ Controls

In addition to the pollutant and source dependent variations, the impact of the IAQ controls on the concentration due to a single source varied greatly from case to case. For example, the reduction for the floor source ranged from 3% to 69%. One reason for the variation was dependence on HVAC system run-time.

Figure 8 shows both the average percent reduction in baseline Floor-VOC concentration due to the HRV and the average percent system run-time for the Miami cases. As shown by the building air change results, the system run-time is an important factor for these IAQ controls

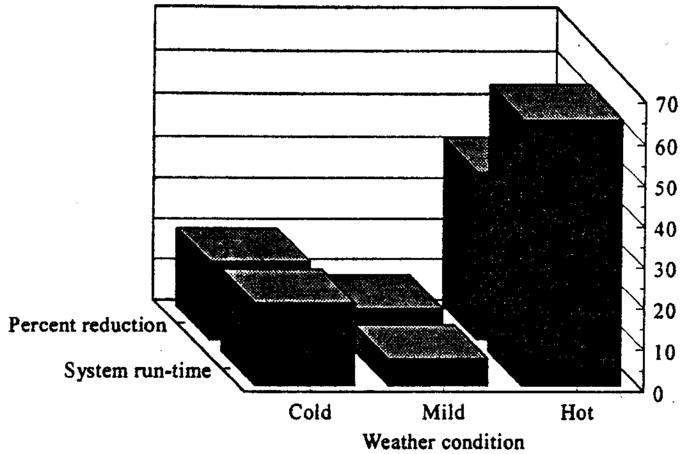


Figure 8 - Influence of System Run-time on IAQ Control Impact (Floor-VOC for Miami HRV Cases)

which were specified to operate only in conjunction with the system. On the mild day, the system operated an average of 7% of the time to meet the low thermal load and reduced the baseline concentration by only 8%. On the hot day, the system operated 65% of the time to meet the high heating load and reduced the baseline concentration by 41%. Although this influence was observed for most sources and cases, other factors, such as timing of system operation, also become important for short-duration sources.

Often, the conditions (small indoor-outdoor temperature difference) causing low system run-time also correspond to low infiltration 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 $\mu g/m^3$) 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 $\mu g/m^3$ and 18,600 $\mu g/m^3$, 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 system run-time. The system run-time limitation could be overcome through other control options (e.g. constant operation, demand control, or scheduled operation) or through other approaches to residential ventilation.

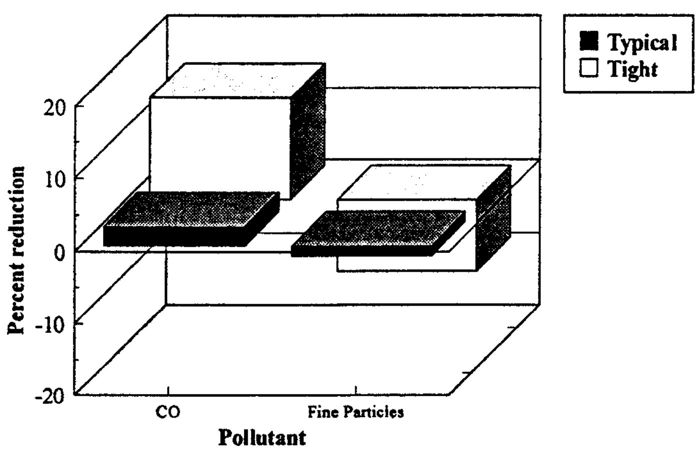


Figure 9 - Influence of envelope airtightness on IAQ control impact (average percent reduction of oven pollutants due to HRV)

Another factor showing a consistent influence on the IAQ control impacts was envelope airtightness. Figure 9 shows the average impact of the HRV on baseline CO and fine particle concentrations due to the oven. The HRV consistently had a larger impact, whether positive or negative, in the tight houses due to a greater relative change in the average building air change rates for the tight houses.

4. IAQ Modeling Issues and Follow-up Activities

An important goal of the project was to identify issues related to the reliability and usefulness of multizone IAQ models and to identify important areas for follow-up work. Several such issues were identified in planning the study, performing simulations, and analyzing the results. Follow-up activities to address these issues are discussed briefly below.

- Model validation - A systematic approach to multizone model validation that considers the types of models, building features, pollutants and sources is needed. Although absolute validation of a program such as CONTAM is impossible, empirical evaluation of a model's predictions is important to establish its range of applicability, to reduce the potential for large errors, and to verify that it correctly predicts trends of interest. While a number of multizone airflow and pollutant transport model validation efforts have been conducted, the efforts to date have not been sufficient to identify the situations in which such models will perform reliably and the situations where they are expected to be less reliable.

- Experimental evaluation - An issue related to model validation but specific to this project is the experimental evaluation of the IAQ controls that were modeled. Even a limited experimental effort would lend support to the model results or indicate deficiencies in the modeling method or details.

- Sensitivity analysis - The modeling results show that the outcome of a simulation varies dramatically for different input values due to the complexities of airflow and pollutant transport in multizone systems, and that the relationships between model inputs and outputs can be unexpected and difficult to understand based only on one's intuition. In this study, attempts were made to select reasonable values for all of the inputs, but the range of reasonable values is quite large for many inputs and some uncertainty in the input values will always exist. Therefore, it is critical to understand which model inputs are most important to the results of a given simulation.

- Development of database for model parameters - In the process of setting up the houses in CONTAM93, difficulties were encountered in obtaining data for many model parameters. Specific inputs that were particularly problematic include, but are not limited to, leakage areas of building components, wind pressure coefficients, particle and NO_2 decay rates, VOC source strengths, and VOC sink characteristics. The lack of a reliable database for model inputs is not a new problem, but it can limit the usefulness of airflow and IAQ models. Existing knowledge gaps need to be identified and analyzed, and a strategy should be developed to obtain the information needed to make modeling a more useful tool.

- Investigation of options to identify/eliminate input errors - Describing a building as a multi-zone system of airflow and pollutant transport elements can be a very complex process, depending on the configuration of the building and the factors being considered in the simulation. Use of any simulation program involves the risk of inputting erroneous numerical values or neglecting to input an individual element. Given the fact that the results of a simulation may not be intuitive, it may be far from obvious that an input error has occurred. This problem is particularly serious for the less experienced modeler who is more likely to make an error and less likely to recognize its existence. It is not clear what features could be developed to identify input errors, but this issue merits attention as these programs are more widely used.

- Simulation of other buildings, pollutants, and IAQ control technologies - The factors included in the simulations were limited by project resources and because it was a preliminary assessment. The modeling approach could be used to investigate many other factors including other house characteristics, pollutants and sources, IAQ controls, and side-effects of implementing the controls. These control options could and ultimately need to be evaluated in several other respects including equipment and installation costs, energy impact, and the potential impacts on the concentrations of other pollutants such as indoor humidity. The consideration of side-effects is important to evaluating the appropriateness of IAQ controls. Some of these issues could be addressed with the current version of CONTAM93, while others may require the development of additional simulation capabilities as discussed below.

- Development of representative building set - It will always be difficult to generalize the results of such simulations or to predict their impact on the residential building stock without considering the wide variety of house types and building features. Development of a set of houses to represent the building stock of a particular region or country based on a statistical analysis of important residential buildings features would make such generalizations more appropriate.

- Development of additional simulation capabilities - Despite the limitations of IAQ modeling discussed here, these programs have the potential to provide valuable insight into a range of IAQ issues. The IAQ issues that can be studied by a program are determined by its simulation capabilities. In addition, these capabilities determine the ability of the model to consider the potential side-effects of an IAQ control method. All models are limited in their capabilities, and opportunities exist to expand these models to consider other issues, or to consider them more thoroughly. Some important additional capabilities include more complete treatment of chemical reaction and absorption phenomena, more detailed HVAC system models to enable realistic consideration of system interactions, thermal analysis to enable the determination of energy impacts, and exposure analysis.

5. Conclusions

The multizone program CONTAM93 was used to simulate the impact of several modifications to typical residential HVAC systems on pollutant concentrations due to a variety of sources in eight houses under different weather conditions. Although the system modifications reduced pollutant concentrations in the houses for some cases, the HRV and OAID increased pollutant concentrations in certain situations involving a combination of weak indoor sources, high outdoor concentrations, and indoor pollutant removal mechanisms. Limited system run-time during mild weather was identified as a limitation of IAQ controls that operate in conjunction with typical forced-air systems. However, this limitation could be overcome through other control options for these devices or through other approaches to residential ventilation. Recommendations for future research include: additional simulations for other buildings, pollutants, and IAQ control technologies; model validation; model sensitivity analysis; and development of a database of important model inputs.

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