Optimization of Ventilation Energy Demands and Indoor Air Quality in High-Performance Homes

Diana E. Hun and Som S. Shrestha, Oak Ridge National Laboratory
Mark C. Jackson, The University of Texas at Austin

ABSTRACT

High-performance homes require that ventilation energy demands and indoor air quality (IAQ) be simultaneously optimized. We attempted to bridge these two areas by conducting tests in a research house located in Oak Ridge, TN, that was 20 months old, energy-efficient (i.e., expected to consume 50% less energy than a house built per the 2006 IRC), tightly-built (i.e., natural ventilation rate ~0.02 h^{-1}), unoccupied, and unfurnished. We identified air pollutants of concern in the test home that could generally serve as indicators of IAQ, and conduced field experiments and computer simulations to determine the effectiveness and energy required by various techniques that lessened the concentration of these contaminants. Formaldehyde was selected as the main pollutant of concern among the contaminants that were sampled in the initial survey because it was the only compound that showed concentrations that were greater than the recommended exposure levels. Field data indicate that concentrations were higher during the summer primarily because emissions from sources rise with increases in temperature. Furthermore, supply ventilation and gas-phase filtration were effective means to reduce formaldehyde concentrations; however, exhaust ventilation had minimal influence on this pollutant. Results from simulations suggest that formaldehyde concentrations obtained while ventilating per ASHRAE 62.2-2010 could be decreased by about 20% from May through September through three strategies: 1) increasing ASHRAE supply ventilation by a factor of two, 2) reducing the thermostat setpoint from 76 to 74°F, or 3) running a gas-phase filtration system while decreasing supply ventilation per ASHRAE by half. In the mixed-humid climate of Oak Ridge, these strategies caused increases in electricity cost of ~$5 to ~$15/month depending on outdoor conditions.

Introduction

High-performance homes require that ventilation energy demands and indoor air quality (IAQ) be simultaneously optimized. Researchers have primarily addressed these two areas independently because of the assumption that their goals have to be mutually exclusive. This assumption is based on the fact that the typical mechanism to reduce the concentration of indoor air pollutants has been dilution through increased ventilation, which causes higher energy consumption by heating, ventilation, and air conditioning (HVAC) units. High-performance homes aim to provide the essential energy end-uses (for example, water heating, refrigeration, space heating, and air conditioning) in an energy-efficient manner. Supplying adequate IAQ should be among these essential energy end-uses because exposure to pollutants that are generated in homes can have detrimental health effects (Adgate et al. 2004; Hun et al. 2009). Consequently, we investigated means to optimize the concentration of indoor air pollutants and ventilation energy demands. To this end, we conducted tests in a research house located in Oak Ridge, TN, that was 20 months old, energy-efficient (i.e., expected to consume 50% less energy

than a house built per the 2006 International Residential Code), airtight (i.e., natural ventilation rate ~0.02 h^{-1}), unoccupied, and unfurnished. Our evaluation consisted of identifying air pollutants of concern in the test home that could generally serve as indicators of IAQ, and conducting field experiments and computer simulations to determine the effectiveness and energy required by various techniques that lessened the concentration of these contaminants.

An initial survey was performed to identify pollutants of concern in the test home. Sampled air was analyzed for volatile organic compounds (VOCs) and aldehydes typically found in residences. Results identified formaldehyde as the main pollutant of concern in the test facility; therefore, subsequent experiments focused on reducing indoor formaldehyde concentrations although the evaluated strategies will likely be effective in lessening VOC concentrations as well. The three strategies that were evaluated through field experiments were increased continuous supply ventilation, increased continuous exhaust ventilation, and gas-phase filtration. Computer simulations focused on supply ventilation, filtration and decreasing indoor temperature setpoints. Findings indicate that improving IAQ in high-performance homes may cause minimal to modest increases in energy use.

Methodology

Test House

The test facility is located in Oak Ridge, TN. The house has two stories and a conditioned basement that is partially below grade, with a total conditioned footprint of 3,710 ft^2 and volume of 45,170 ft^3. Table 1 lists the materials used in the building envelope. The HVAC system consisted of a 2 ton water-to-air-source heat pump with a rated cooling and heating coefficient of performance (COP) of 5.4 and 4, respectively.

Volatile Organic Compounds and Formaldehyde

VOCs and formaldehyde were monitored through active sampling. VOCs were collected using Supelco thermal desorption tubes packed with Carbotrap. Formaldehyde was sampled with SKC 2,4-dinitrophenylhydrazine (DNPH) silica gel cartridges with potassium iodide ozone scrubbers. Air was drawn through the Supelco tubes and DNPH cartridges with pumps; flow rates were measured at the beginning and end of a monitoring session with a Bios Defender 530 dry calibrator. Most monitoring periods lasted close to 24 hours to capture diurnal effects and air was sampled at a rate of ~200 cc/min. Additionally, 1-hr and 2-hr air samples were collected at higher flow rates (~500 cc/min) to examine the decrease of formaldehyde during tests (i.e., implementation of increased supply or exhaust ventilation, or gas-phase filtration), and the increase of formaldehyde after tests. Air samples were analyzed at Matrix Analytical Laboratories, Inc., in Farmers Branch, TX, following a modified version of the Environmental Protection Agency method EPA TO-11a for formaldehyde (EPA 1999a). Similarly, a modified version of EPA TO-17 was used for VOC analyses (EPA 1999b). Real-time formaldehyde measurements were also gathered every 30 minutes with Shinyei colorimetric monitors to improve the resolution on the effects from increased ventilation, gas-phase filtration, and diurnal environmental cycles on indoor concentrations.

Table 1. Building envelope materials

Building Envelope Components	Materials
Basement Walls	
Framing	12" concrete walls
Exterior insulation	2-3/8" rigid fiberglass
Waterproofing	Fluid-applied membrane
Above grade cladding	Stone
Walls	
Interior sheathing	Gypsum board
Framing	2×6 wood studs at 24" on center
Insulation ($ft^2 \cdot °F \cdot h/Btu$)	R-22: R-19 fiberglass batt and ½" closed-cell foam (R-3)
Exterior sheathing	Oriented strand board
Water resistive and air barrier	Fluid-applied membrane
Cladding	Fiber cement siding and stacked stone
Windows	Triple pane windows
Roof / Sealed Attic	
Framing	2×10 wood rafters at 24" on center
Roof deck insulation ($ft^2 \cdot °F \cdot h/Btu$)	R-50: foil faced, aged phenolic boards
Sheathing	Oriented strand board
Underlayment	Felt paper
Roof deck ventilation	Soffit and ridge vents
Cladding	Infrared reflective standing seam metal

Ventilation Rates

Ventilation or air exchange rates (AER) were estimated with the tracer gas decay method. Real-time data were sampled and analyzed with an Innova 1303 multipoint sampler/doser and an Innova 1412 photoacoustic gas analyzer, respectively. The tracer gases used were 1,1,1,2-tetrafluoroethane ($C_2H_2F_4$, also known as the freon R134a), and sulfur hexafluoride (SF_6) to a lesser extent; their respective detection limits at 68°F are 11 and 10 ppb. In addition to R134a and SF_6, the analyzer also monitored water vapor and other fluorinated compounds to compensate for interference. Tracer gas was sampled every two minutes, and the total sampling period varied per test and lasted a minimum of two hours. The air within the living area of the house was well-mixed by keeping the HVAC fan running continuously. Uniform mixing was verified by simultaneously sampling the tracer gas at the first and second floors, and ensuring that their concentrations were within 10% of each other.

Supply and Exhaust Ventilation

Continuous supply and exhaust ventilation, without gas-phase filtration, were provided with a portable blower (Amaircare Airwash Whisper 675 or Lennox HEPA-60) that was attached to a window with a flex duct (Figure 1A). The airflow rate through the blower was regulated with a variable speed controller, and the air exchange rate produced by the blower was estimated with the whole-house tracer gas decay method.
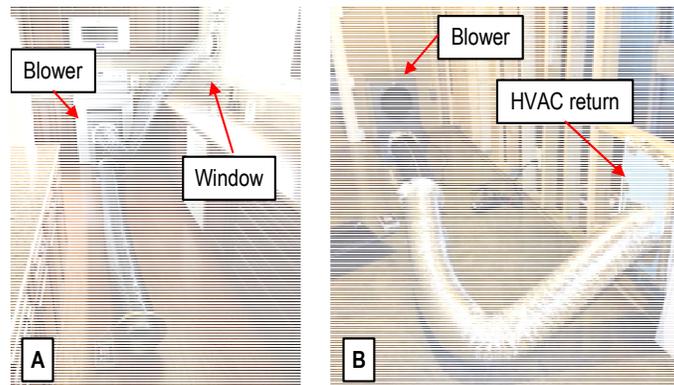
Figure 1A. Supply and exhaust ventilation setup: blower attached to a window. Figure 1B. Gas-phase filtration setup: air treated through a blower with a filtration canister and distributed through the HVAC return.

Gas-Phase Filtration

Air in the house was treated with gas-phase filters in portable blowers. Two blowers were used: Amaircare Airwash Whisper 675 and Lennox HEPA-60. Both blowers had a canister with 30 lb of filtering material composed of activated coconut-shell carbon with a proprietary additive to diminish formaldehyde concentrations. Each blower, with the installed canister, was operated at a flow rate of ~375 cfm, with an average power usage of 0.54 W/cfm. The blower outlets were attached to the HVAC return grills so the central fan would distribute the filtered air throughout the house (Figure 1B). The single-pass efficiency of the canisters was estimated by gathering DNPH air samples upstream and downstream of the filtration unit. Also, the removal efficiency of the canisters was calculated using the decaying formaldehyde concentrations that were collected from the test house immediately after filtration was initiated.

Multivariate Regressions

MatLab R2012a was used to conduct multivariate regressions that predict indoor formaldehyde concentrations. Variables considered in the regressions were indoor temperature and relative humidity, outdoor temperature, and ventilation rate (i.e., natural plus mechanical). Twenty-four hour averages were used with all of these variables except AER because its evaluation periods were shorter. Due to tight construction, AER measurements were relatively stable as long as changes in outdoor conditions were not large.

Simulations

An EnergyPlus model was generated using version 7.2.0.006. This software estimates infiltration rates using weather files for specific geographical locations. In order to improve these estimates, the coefficient that is used by the software to calculate natural ventilation was calibrated with AERs that were measured while the mechanical ventilation system was shut down. The authors are aware that the ideal calibration procedure would have involved improving the EnergyPlus code that is used to compute natural ventilation instead of modifying the infiltration coefficient; however, this was beyond the scope of this project. The calibrated EnergyPlus model was combined with the derived multivariate equation to predict monthly formaldehyde concentrations, HVAC loads, and energy cost.

Results and Discussion

Air samples were collected in November 2011 to identify pollutants of concern while the house was supplied 30 cfm (0.04 h^{-1}) of mechanical ventilation with an energy recovery ventilator. These samples were analyzed for VOCs and aldehydes typically found in homes. Results indicate that the monitored VOCs were well below the recommended exposure levels (REL) set by the National Institute for Occupational Safety and Health (NIOSH 2012) and/or the state of California Office of Environmental and Health Hazard Assessment (OEHHA 2012). This is likely because many of the typical sources that emit these compounds (e.g., gasoline, solvents, fragrances, cleaners) are not present in unoccupied houses in significant quantities. Among the aldehydes that were monitored during the exploratory survey, only the formaldehyde measurement of 49 ppb exceeded the RELs set by NIOSH (8-hr exposure: 16 ppb) and OEHHA (8-hr exposure: 7.3 ppb), which are the strictest recommended levels worldwide. Other RELs include: Canada = 40 ppb (long-term exposure; Health Canada 2014), Norway = 50 ppb (24-hr; Salthammer, Mentese, and Marutzky 2010), and World Health Organization = 81 ppb (30-minute; WHO 2010).

Given the aforementioned results, we selected formaldehyde as the main pollutant of concern in the test home. Indoor formaldehyde concentrations (C_{in}) collected throughout 2012 ranged from 27 ppb in the winter to 74 ppb in the summer. Higher summer C_{in} values were encountered primarily because emission rates from sources rise with increases in temperature, and to a lesser extent because natural ventilation decreases with lower indoor-to-outdoor temperature differentials. Relative humidity could also have been influential but was not investigated because it can take days or weeks for formaldehyde emissions from sources, such as composite wood, to reach equilibrium after a change in humidity (Myers 1985). Pressed-wood products used for framing (Kelly, Smith, and Satola 1999), cabinetry and passage doors (Hodgson, Beal, and McIlvaine 2002) were likely the main source of formaldehyde in the test home because it was unfurnished and unoccupied. The measured concentrations were in the same range as those observed by Offermann (2009) in a recent study of California homes (50th ptile = 29 ppb, 95th ptile = 77 ppb). Reducing pressed-wood products in new homes is the most effective mechanism to lower C_{in}, but this solution may not be practical in existing residences.

Figure 2 shows formaldehyde concentrations and indoor temperatures collected during tests to evaluate the effectiveness of supply ventilation, exhaust ventilation, and gas-phase filtration. The DNPH measurements in Figure 2A indicate that increasing supply ventilation from 15 to 284 cfm caused 24-hr formaldehyde values to decrease from 55 to 24 ppb. In contrast, Figure 2B shows that increasing exhaust ventilation from 9 to 118 cfm either had limited influence or exacerbated 24-hr C_{in}: formaldehyde decreased from 58 to 54 ppb on the first day, and increased to 67 ppb on the second day. These results suggest that exhaust ventilation is not as effective in reducing C_{in} as supply ventilation probably because the former induces airflows that transport pollutants within the cavities of exterior walls into the living area, which would make dilution of indoor contaminants with fresh air less effective. Rudd and Bergey (2013) also reported similar results on the lower performance of exhaust ventilation. More research is needed to evaluate the effectiveness of exhaust ventilation given that, among the various types of residential mechanical ventilation systems, exhaust ventilation is likely the most popular because it can be attained economically with bathroom fans.

DNPH samples in Figure 2C indicate that gas-phase filtration lowered C_{in} from 47 to 16 pbb. As described in a previous publication (Hun, Jackson, and Shrestha 2013), we used the

whole-house concentrations measured while formaldehyde was decreasing due to filtration and calculated a filter removal efficiency (η) of 0.21 in two tests. We also estimated the single-pass removal efficiency by sampling the air upstream and downstream of the filtration system on one occasion; η in this case was 0.85. The reason why the single-pass efficiency method yielded a filter removal efficiency that was four times higher than what was obtained through the whole-house method may be explained by the fact that the latter method included the interactions that formaldehyde experiences in a realistic setting (e.g., continuous variations in emission rates due to changes in temperature and ventilation, and sorption to building materials), while the former method did not.
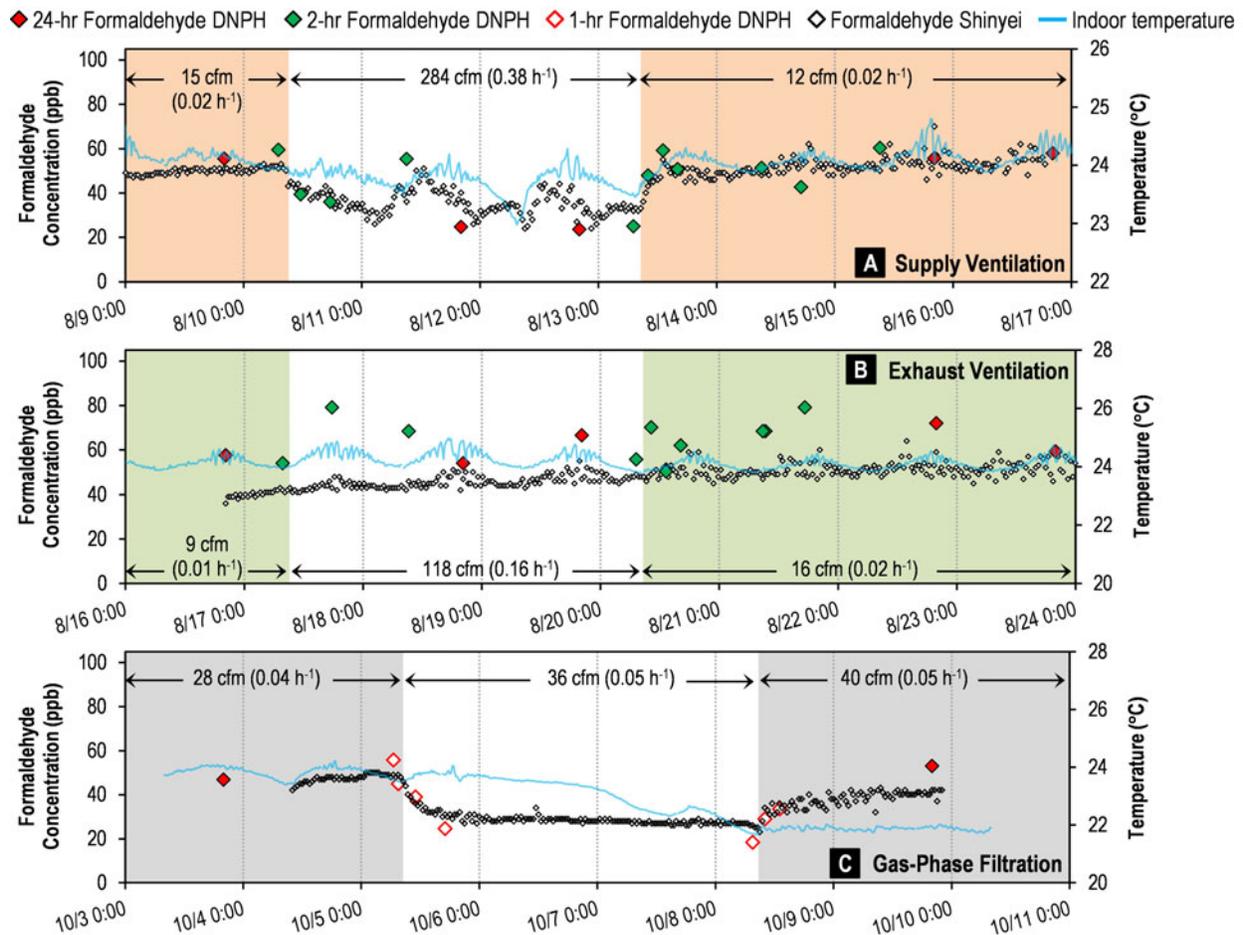
Figure 2. Formaldehyde concentrations and indoor temperature measured during tests to evaluate A) supply ventilation, B) exhaust ventilation, and C) gas-phase filtration.
a.   DNPH concentrations are shown halfway through their sampling period.
b.   Air exchange rates shown are due to natural and mechanical ventilation.

We conducted multivariate regressions using field data from the supply ventilation test to evaluate the influence of indoor (T_{in}) and outdoor temperature, indoor relative humidity, and ventilation rate on C_{in}. Although informative, the following results should be interpreted with caution because they were obtained from a new unoccupied and unfurnished residence; therefore, these findings are not meant to be used to make generalizations of the housing stock. The derived equation for 24-hr average formaldehyde concentrations is:

$$C_{in} = -90.4\text{AER} + 9.43T_{in} - 2747 \qquad (p < 0.001) \qquad [1]$$

where the units for C_{in}, AER and T_{in} are ppb, h^{-1} and Kelvin, respectively. Both AER and T_{in} are statistically significant predictors of formaldehyde concentrations ($p < 0.001$) at the evaluated indoor conditions: $73.0°\text{F} \le T_{in} \le 82.3°\text{F}$, $0.01 \text{ h}^{-1} \le \text{AER} \le 0.41 \text{ h}^{-1}$ ($8.82 \text{ cfm} \le \text{AER} \le 308$ cfm). Figure 3 illustrates good correlation between the estimated and measured formaldehyde concentrations ($R^2 = 0.82$). For the evaluated temperature range, the observed linear relationship between C_{in} and T_{in} is in agreement with the Berge model (Berge et al. 1980) which estimates formaldehyde concentrations as a function of relative humidity and temperature. Similarly, Equation 1 indicates a linear relationship between C_{in} and AER for the range of air exchange rates that were assessed in this study. The Hoetjer-Berge-Fujii equation for steady-state formaldehyde concentrations (Myers 1984) supports the observed linear dependence of C_{in} on ventilation when it varies between 0.01 and 0.41 h^{-1}. Moreover, Willem et al. (2013) also noted this trend after monitoring these two variables in new US homes.
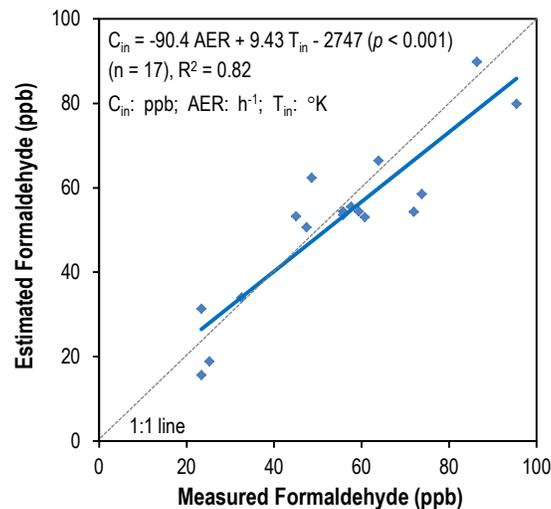
Figure 3. Measured and estimated 24-hr average formaldehyde concentrations.

We incorporated Equation 1 into an EnergyPlus model to evaluate the cost-effectiveness of strategies that could be used to decrease C_{in}. Major assumptions in the models include:

a. Well-mixed indoor environment
b. The regression equation that was derived with 24-hr average C_{in} and T_{in} can be used to estimate 1-hr formaldehyde emission rates and concentrations
c. Outdoor formaldehyde concentration = 2 ppb
d. No formaldehyde sinks
e. Filtration system:
   η (filter removal efficiency) = 0.21
   Q_f (flow rate through filtering device) = 375 cfm
   Energy use = 0.54 W/cfm $\times$ 375 cfm = 203 W

The four cases we explored are summarized in Table 2. Case 1 served as the baseline scenario with ventilation rates per ASHRAE 62.2-2010 and thermostat setpoints per the Building America protocol (Hendron and Engebrecht 2010); Case 2 decreased the cooling setpoint by 2°F during the cooling season; Case 3 increased the ASHRAE mechanical ventilation rate by a factor of two; and Case 4 employed gas-phase filtration and decreased the ASHRAE ventilation by half. Also, in all the simulations we used the 2012 weather data that we collected at the test site in Oak Ridge, TN, and we assumed the electricity cost to be $0.10/KWh.

Table 2. Cases simulated with EnergyPlus

Case	Mechanical Supply Ventilation (cfm, h^{-1})	Indoor Temperature (°F)	Gas-Phase Filtration
1 (Baseline)	ASHRAE 62.2 = 75, 0.1	Building America Protocol: Heating set point = 71 Cooling set point = 76	-
2	ASHRAE 62.2 = 75, 0.1	Heating set point = 71 Cooling set point = 74	-
3	2 × ASHRAE 62.2 = 150, 0.2	Building America Protocol: Heating set point = 71 Cooling set point = 76	-
4	0.5 × ASHRAE 62.2 = 38, 0.05	Building America Protocol: Heating set point = 71 Cooling set point = 76	$\eta\, Q_f/V = 0.11\ h^{-1}$

Figure 4 summarizes the monthly and annual estimates from the EnergyPlus simulations. In general, HVAC loads and energy costs were higher during the winter season, followed by the summer months, due to larger indoor-to-outdoor temperature differentials. Additionally, C_{in} values were greater during the warmer months, and these lessened with seasonal changes such as decreases in T_{in} and increases in infiltration due to larger indoor-to-outdoor temperature differentials. Results from the baseline case suggest that summer concentrations exceeded winter values by a factor of two (July = 51 ppb, January = 24 ppb). The more specific results that follow were highly influenced by the fact that the test house had a tightly built envelope, was well insulated, had a very efficient HVAC unit, and was located in a mixed-humid climate.

Increased supply ventilation and gas-phase filtration lowered the annual average formaldehyde concentration from 36 ppb (baseline case) to about 27 ppb, at an energy cost of $140/year and $115/year, respectively. The annual average concentration was higher in Case 2 (32 ppb) than in Cases 3 and 4, because changing the cooling setpoint is only applicable during the cooling season; consequently, the electricity cost penalty was $40/year. Results also indicate that cutting the ventilation rates by 50% of what is required by ASHRAE lowered annual energy penalties by 8.6 MBtu ($60/year). These findings suggest that in the evaluated test house, aiming for lower than the ASHRAE ventilation rates provides minimal energy benefits that would be easily canceled out by the energy use of a filtration system as shown in Figure 4.

Results imply that efforts to lower exposure to formaldehyde would be of more consequence from May to September. Figure 5 shows modeling results when the proposed strategies are only implemented during these months. Here, Cases 2, 3 and 4 yielded similar results: C_{in} decreased by about 20%, while causing energy cost penalties that ranged from ~$5 to ~$15/month depending on the outdoor temperatures.
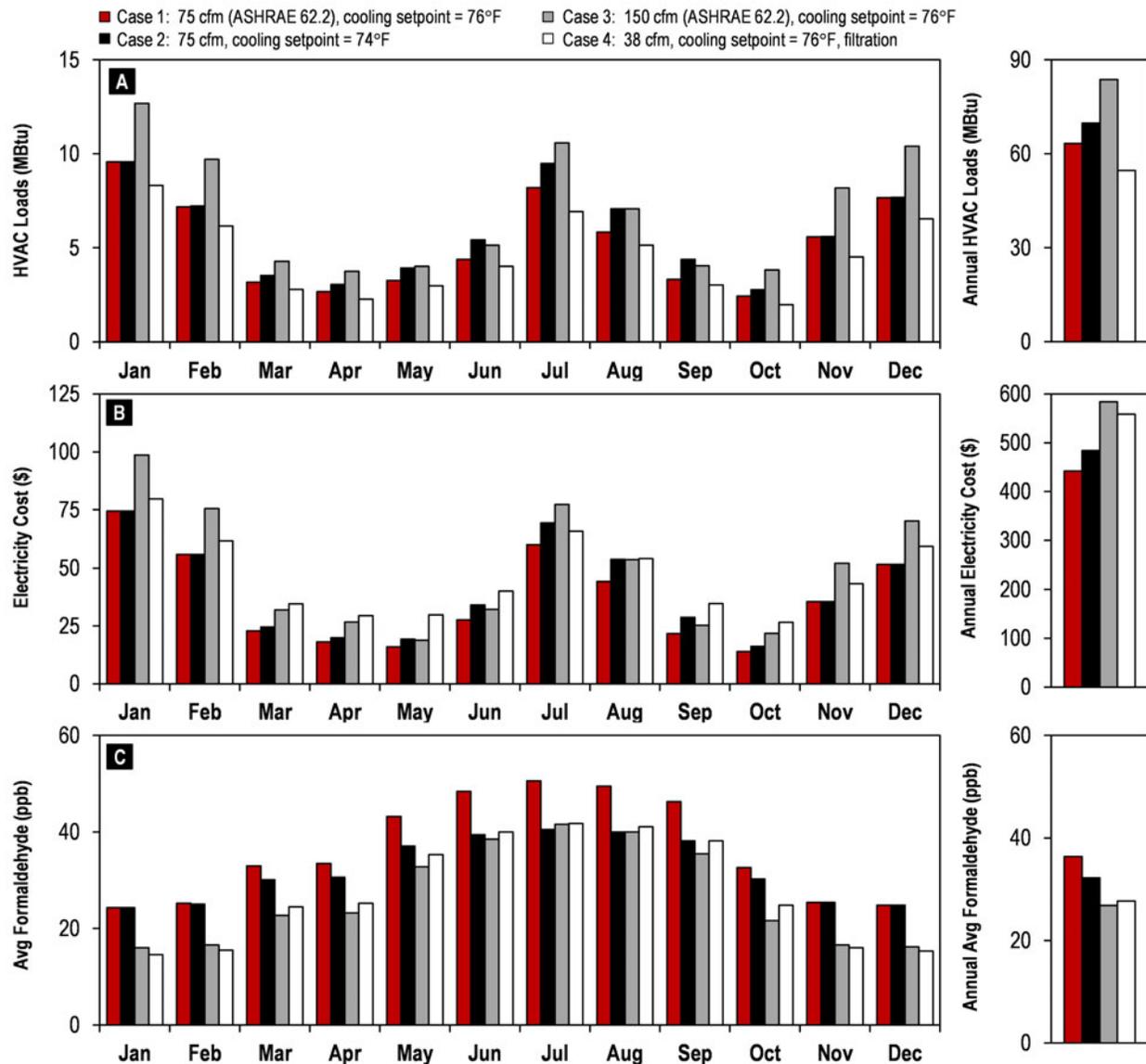
Figure 4. Simulation results for a house in Oak Ridge, TN. A: HVAC latent and sensible loads. B: Electricity costs due to HVAC and filtration systems. C: Formaldehyde concentrations.

Each of the investigated strategies poses advantages and disadvantages. Lowering the cooling setpoint requires no capital cost, focuses on the months when formaldehyde emissions are the highest, and lowers absolute humidity during the summer when it tends to be the highest. A major drawback of this strategy is that it would increase energy demand during the time of day when utilities experience their peak loads.

Increasing mechanical ventilation rates will help with the reduction of contaminant concentrations due to emissions from long-term sources of pollutants. This strategy will not require significant additional capital cost in tightly-built homes other than installing a larger outdoor air intake duct than what is required to meet ASHRAE's minimum ventilation rates. Disadvantages from higher mechanical ventilation include that it will increase latent loads in the summer, which could be difficult to manage by HVAC units without a dedicated

dehumidification system. Furthermore, energy penalties during the winter are significantly higher, but it could be argued that increased mechanical ventilation is not needed during the heating season because of lower indoor concentrations and greater infiltration.
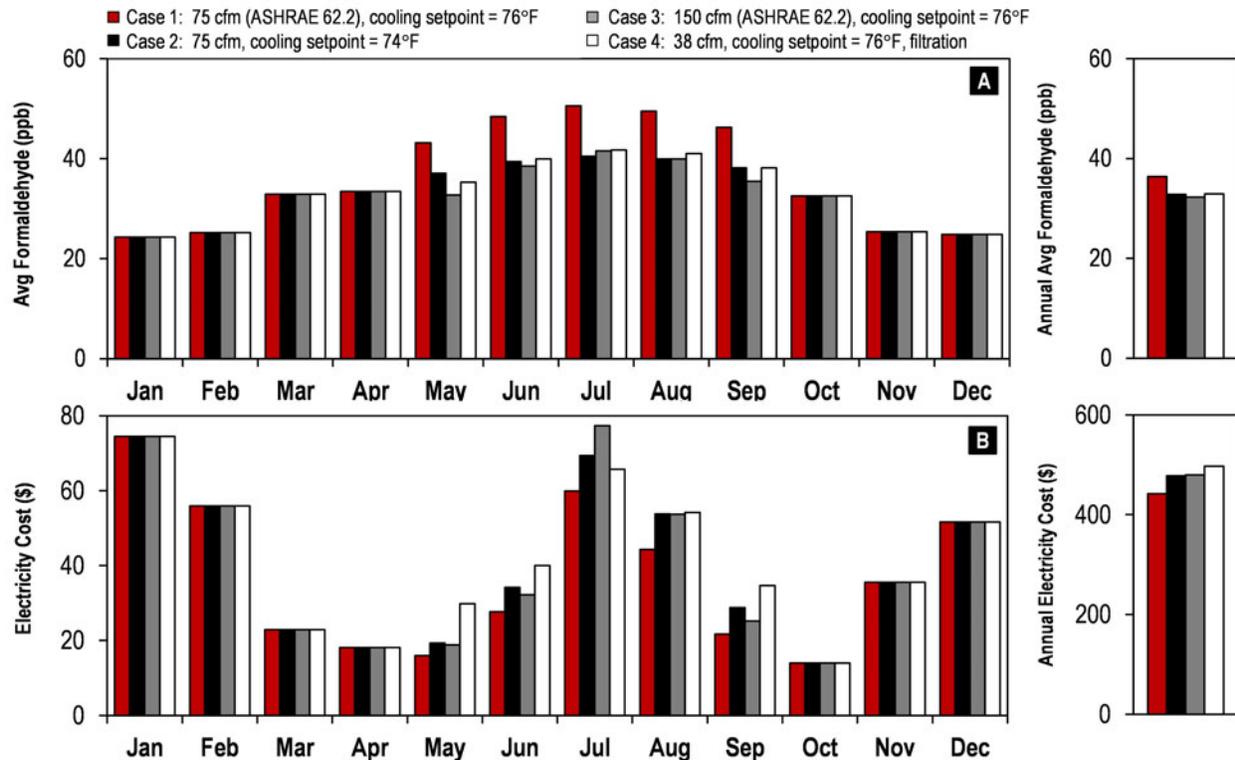
Figure 5. Optimized case for a house in Oak Ridge, TN. A: Formaldehyde concentrations. B: Electricity costs due to HVAC and filtration systems.

In addition to lowering formaldehyde concentrations, the gas-phase filtration system also lessens VOC concentrations. Moreover, by allowing lower ventilation rates, the filtration system reduces indoor concentrations of pollutants that are generated outdoors, and decreases indoor moisture levels during the summer given that outdoor sources are dominant during this period. However, this system has an initial capital cost of ~$2800, the price to replace the carbon canister is on the order of $625 per year, and the system consumes 200W or about $180 per year.

Conclusions

Formaldehyde remains a pollutant of concern in new homes. Concentrations from a high-performance test house (i.e., tightly-built envelope, good insulation, and efficient HVAC unit), that was unfurnished and unoccupied, showed seasonal variations of 27 ppb to 74 ppb. Likely formaldehyde sources include pressed-wood products used to frame houses, cabinetry, and passage doors. Concentrations were higher during the summer months primarily because emission rates from sources rise with increases in temperature, and to a lesser extent because natural ventilation decreases with lower indoor-to-outdoor temperature differentials. Supply ventilation and gas-phase filtration were effective means to reduce indoor formaldehyde concentrations; however, exhaust ventilation had minimal influence on this pollutant.

Results from simulations suggest that formaldehyde concentrations obtained while ventilating per ASHRAE 62.2-2010 could be decreased by ~20% from May through September through three strategies: 1) increasing ASHRAE supply mechanical ventilation by a factor of two, 2) reducing the thermostat setpoint from 76 to 74°F, or 3) running a gas-phase filtration system while decreasing mechanical supply ventilation per ASHRAE by half. In the mixed-humid climate of Oak Ridge, TN, these strategies caused increases in electricity cost of ~$5 to ~$15/month depending on outdoor conditions. It may be possible to propose decreasing ASHRAE mechanical ventilation rates during the winter because of seasonal increases in infiltration and because emission rates from various sources of pollutants, such as formaldehyde, are likely to be lower. However, this is contingent upon reaching a consensus on acceptable contaminant levels in homes. These suggestions could lead to significant savings, because winter ventilation energy demands are usually higher than those from other seasons throughout most of the country.

Acknowledgments

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