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Effect of Residential Ventilation Techniques for Hot and Humid Climates on Indoor Concentrations of Volatile Organic Compounds

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Abstract

Mechanical ventilation may be necessary to provide adequate ventilation in new houses due to the relatively low rates of infiltration achieved in new construction. However, in hot and humid climates, increased ventilation may raise indoor humidity to an undesirable level. A study was undertaken by the Florida Solar Energy Center (FSEC) to evaluate the humidity effects of different mechanical ventilation strategies for such climates. The study was conducted in a new 141-m^2 manufactured house sited at the FSEC campus. Six mechanical ventilation strategies were evaluated for their ability to control indoor humidity levels over 14-day periods with simulated occupancy. A base case with no extra ventilation served as a control. The strategies consisted of spot exhaust ventilation, use of an energy recovery ventilator, and four configurations of a dedicated outdoor air supply system, one of which included use of a room dehumidifier.

The objective of the study described here was to determine the impacts of the ventilation techniques on the concentrations and emission rates of indoor-generated formaldehyde and other volatile organic compounds (VOCs). Measurements of indoor and outdoor VOCs were made both by active and passive sampling during each ventilation condition. The emission factors of most VOCs remained relatively constant across all experiments with mechanical ventilation. The case with the dehumidifier and the outside air supply fan programmed to be on at least one-third of the time was shown to provide the generally lowest indoor VOC concentrations because

it was able to operate at a higher ventilation rate while maintaining 50% indoor relative humidity.

Key Words: ***Air change rate, Dehumidification, Formaldehyde, Manufactured House, Relative Humidity***

Introduction

A recent nationwide trend in new residential construction has been to make house envelopes tighter by reducing the sources of uncontrolled air leakage (Sherman and Matson, 2002). As a consequence, ventilation rates in new houses likely are lower than historically measured values such as reported by Murray and Burmaster (1995). Thus, supplemental ventilation systems and other techniques to increase ventilation are needed in new houses to better remove air contaminants generated indoors and to reduce potential exposures of occupants to these contaminants. In fact, the ASHRAE new residential ventilation Standard 62.2-2003 (ASHRAE, 2003), which is intended to ensure minimum acceptable indoor air quality, requires in most cases that a fan be used to provide whole-house ventilation (Sherman, 2004).

Volatile organic compounds (VOCs) comprise an important class of indoor-generated air contaminants that includes such toxicants as formaldehyde, acetaldehyde, toluene and other aromatic solvents, phenol, and naphthalene. For common VOCs emitted by the building envelope, concentrations generally decrease with increasing outdoor air change rates. The decreases typically are proportional to air change rate for the most volatile compounds, while the concentrations of lower volatility compounds are less affected due to increases in their net emission rates with increasing air change rate (Hodgson et al, 2004). Thus, increased ventilation is effective for limiting indoor concentrations and exposures of many, but not all, important VOCs.

However, increased ventilation in hot and humid climates may have the deleterious effect of raising indoor humidity levels. Elevated indoor moisture has been linked to incidences of building failure (Moyer et al., 2001), to elevations in formaldehyde concentrations (Matthews et al., 1986), and to effects on occupants such as asthma, allergic symptoms and airway infections (Bornehag et al., 2004). Thus, a study was undertaken by the Florida Solar Energy Center (FSEC) in a new manufactured house to determine the indoor humidity effects and energy consequences of different ventilation techniques potentially applicable to new houses in hot and humid climates (Moyer et al., 2004). This study quantified indoor humidity and energy use for a base-case condition without supplemental ventilation and for six conditions employing readily available mechanical ventilation techniques. These were a single exhaust-only system and five supply-based systems, one of which additionally employed dehumidification. Indoor occupancy was simulated during the 14-day experimental periods by computer control of lights, appliances, and showers.

The study reported here was conducted in concert with the ventilation study. The objective was to determine the impacts of the different ventilation techniques on the concentrations and emission rates of indoor-generated formaldehyde and other VOCs.

Methods

Description of Study House and Ventilation Techniques

Moyer et al. (2004) have described the manufactured study house and the six mechanical ventilation techniques that were tested. Briefly, the house is a doublewide, three bedroom, two bathroom structure, built to U.S. Department of Housing and Urban Development (HUD) Standards (HUD, 1994). It is Energy Star® rated. The house was manufactured in Florida and was setup in July 2002 at the FSEC site in Cocoa, FL for use as a research and training facility. The floor area is 141 m^2 and the enclosed air volume is 326 m^3. The ventilation rate in air changes per hour induced by fan pressurization at 50 Pa (ACH_{50}) was 5.4 h^{-1}. This is approximately equivalent to a normalized leakage (NL) of 0.3 cm^2 per m^2 of floor area (Sherman and Dickerhoff, 1998), which is the about average for new conventional houses (Sherman and Matson, 2002). The walls of the house are painted gypsum board; much of the floor area is carpeted; the remaining floor area in the kitchen, utility area and the small bathrooms is ceramic tile; and only a few furnishings are present. For this study, the heating and air conditioning (HAC) system consisted of an under-floor duct system connected to a split system air conditioner (30.2 kBtu rated cooling capacity) with electric resistance heating located in a closet near the kitchen area. Interior temperature is maintained with an electronic thermostat.

Occupancy of the house by a family of four was assumed and was simulated during the experiments. According to ASHRAE Standard 62.2-2003, the house with this occupancy has a ventilation air change requirement of 0.39 h^{-1} (15 L sec^{-1}/100 m^2 floor area plus 3.5 L sec^{-1}/person). The thermostat held the temperature constant at 23.9° C. To simulate sensible/latent heat generation, major appliances, showers, lighting, and two humidifiers and heat lamps (representing the occupants) were operated by computer control. Environmental parameters (indoor and outdoor temperatures and relative humidity (RH)), HAC system and air handler fan operating parameters, and energy use were continuously monitored.

Each ventilation condition was maintained for 14 days. For the exhaust only ventilation technique, termed “Spot” ventilation, the bathroom and kitchen fans were operated for 30 minutes following each simulated moisture-producing event. For the five supply-based systems, the air handler fan was set to deliver 50 cfm (23.6 L sec^{-1}) of outside air to the return plenum upon demand. For the outside air “OA” technique, air was supplied through a dedicated air duct only when the HAC system was operated, with the quantity of ventilation air determined by air handler run time. For the “Dehumid” and “10/20” techniques, a controller was added to the air handler fan that operated the fan on a 10-minute on and 20-minute off cycle to provide additional scheduled ventilation. In the Dehumid configuration, a standalone dehumidifier set to approximately 50% RH was located near the return air grill. The device is Energy Star® rated at 19 L/day, 1.3 L/kWh. An energy-recovery ventilator, with which outside air to meet the ventilation requirement was drawn through an enthalpy transfer media, was used for the “ERV1” technique. A modified air handler fan control was used for the “Hstat” technique. When dehumidification was called for by the humidistat, the air handler fan was operated at a low speed setting; a higher speed was selected when sensible cooling was needed. Ventilation air was supplied through a duct as described for the 10/20 technique. There also was a base-case condition, termed “None”, in which there was no additional mechanical ventilation.

VOC Sampling and Analysis

During the period of May to September 2003, active sampling for VOCs and aldehydes was conducted for each of the seven ventilation conditions. Generally, the samples were collected on a day in the mid to later portions of the 14-day experiments. During sampling, all exterior windows and doors were closed, all interior doors were open, the air handler fan was operated as described above, and the thermostat maintained indoor temperature. Air samples for VOCs and aldehydes were collected in the central living area between the kitchen and the living/dining room, the master bedroom, and outdoors. The indoor air samples were positioned about 1.5 m above the floor. Field blanks for VOCs and aldehydes were obtained for each sampling event.

Active air samples for VOCs were collected on sorbent tubes (P/N CP-16251, Varian Inc.) modified by substituting a 15-mm section of 60/80-mesh carbon molecular sieve (P/N 10184, Supleco Inc.) at the outlet end. Air was pulled through the sorbent tubes using dual-headed peristaltic pumps. Pump flow rates for VOCs, measured during each sampling period, were about 5 mL min^{-1}. Samples were collected over 180 min (3 h) yielding sample volumes of about 0.9 L. Each sample was collected in duplicate. Field blanks also were included during each sampling period. Active air samples for formaldehyde and acetaldehyde were collected over the same intervals on silica gel cartridges treated with acidified 2,4-dinitrophenylhydrazine (DNPH) (P/N WAT047205, Waters Corp.) using separate peristaltic pumps. Sampling flow rates were about 150 mL min^{-1} collected over 180 min yielding sample volumes of about 27 L.

In addition, passive samples for abundant VOCs and formaldehyde were collected over each of the seven experiments. The passive monitors were continuously deployed over at least 10 days of each 14-day experiment. For VOCs, an organic vapor monitor (OVM) containing a charcoal adsorbent wafer (P/N OVM 3500, 3M Corp.) was employed. A monitor (P/N N571AT, Assay Technology, Inc.) using the same DNPH chemistry as the active aldehyde sampler was employed for formaldehyde. Indoors, the monitors were hung on strings in approximately the same locations and positions used for placement of the active samplers. The outdoor monitors were hung inside an inverted metal bucket attached to an adjacent structure at a height of 2.5 m. A field blank and a duplicate sample were obtained for each passive device in each sampling event.

Active VOC samples were quantitatively analyzed for individual compounds by thermal desorption-gas chromatography/mass spectrometry (TD-GC/MS) (U.S. EPA, 1984). Samples were thermally desorbed and concentrated on a cryogenic inlet system (Model CP-4020 TCT, Varian, Inc.) fitted with a packed trap (P/N CP-16425, Varian, Inc.). The sample desorption temperature was 235 °C for 6.5 min. The cryogenic trap was held at -100 °C, and then heated to 235 °C for injection. The analytical column was 0.25-mm ID, 30-m long with a 1-µm film (14 %-cyanopropyl-phenyl)-methylpolysiloxane bonded phase (P/N 122-0733, Agilent Technologies). The GC oven (Series 6890, Hewlett-Packard) was ramped from 1 to 225 ^{o}C.

The MS (Series 5973, Hewlett-Packard) was operated in electron impact mode and scanned from *m/z* 30 to 350. Multi-point calibrations were created and referenced to an internal standard of 1-bromo-4-fluorobenzene. Approximately 50 target compounds spanning broad ranges of volatility and chemical functionality were quantified.

Passive VOC monitors were quantitatively analyzed for the most abundant individual compounds. For each sample, the charcoal wafer was extracted with 1.5 mL of carbon disulfide (CS_2, 99.9+% redistilled, low benzene, Aldrich Chemical Co., Inc.) spiked with 1-bromo-4-fluorobenzene as an internal standard. The extract was quantitatively analyzed for target VOCs by manually injecting a 1-µL aliquot into the GC/MS system (described above) operated in the split-less injection mode. The oven temperature program was ramped from 25 to 225 C°. Target compounds were quantified using multi-point internal standard calibrations.

The concentrations of the target VOCs in air were calculated from the deployment times and the compound-specific "effective" sampling rates provided by the manufacturer of the monitor (3M, 1999). For some compounds not listed in the technical bulletin, theoretical rates calculated by Shields and Weschler (1987) based on Fick's First Law of Diffusion were utilized. Otherwise, the sampling rate was inferred from the rate for a chemically related compound with similar volatility. Efficiencies for extraction of the target VOCs from the charcoal wafers were not measured. Thus, the concentrations were uncorrected for any incomplete recovery during extraction.

Each active sampling cartridge for aldehydes was extracted with 2 mL of acetonitrile. Passive monitors were extracted with 1 mL of acetonitrile and then diluted to 2 mL with a 35/65% mixture of acetonitrile and water. Active sampler extracts were analyzed for formaldehyde and acetaldehyde by high-performance liquid chromatography with a diode array detector at a wavelength of 365 nm following ASTM D 5197 (ASTM, 1997a). Passive monitor extracts were analyzed only for formaldehyde. Compound masses in the extracts were determined from multi-point calibrations of external standard mixtures. Passively sampled formaldehyde concentrations were calculated from the deployment times and the manufacturer supplied sampling rate.

Air Change Rate

The air change rate during each 3-h active sampling period was determined by measurement of sulfur hexafluoride (SF_6) tracer gas decay using a photo-acoustic infrared analyzer (Model 1302, Brüel & Kjær Instruments, Denmark). Air change rates were calculated as the slope of the least squares linear regression of the natural log of the SF_6 concentration in the central living area.

Data Analysis

Emission rates (ERs) of the target compounds in mass per time ($\mu g\ h^{-1}$) were derived assuming the house was an ideal continuously stirred tank reactor (CSTR) operating at near steady-state conditions (ASTM, 1997b). Net losses of compounds due to factors other than ventilation, e.g., sink effects, were ignored. The steady-state form of the mass-balance model for a CSTR was used:

$$ER = Va\,(C - C_0) \tag{1}$$

where V is the ventilated volume of the house (m^3); a is the air change rate (h^{-1}); C is the air concentration of the compound in the house ($\mu g\ m^{-3}$); and C_0 is the outdoor air concentration ($\mu g\ m^{-3}$). Area-specific emission rates or emission factors (EFs) in mass per area-time ($\mu g\ m^{-2}\ h^{-1}$) were calculated by dividing the corresponding emission rates by the floor area (m^2) of the house.

Results

Eight ventilation experiments were run consecutively from May 16 through September 29, 2003. Moyer et al. (2004, see Tables 1 and 2) summarized the average house and ambient conditions for each ventilation case. The average house and ambient temperature and RH conditions for the seven experiments of interest here are reproduced in Table 1 (Cases 1 – 7; note that no VOC measurements were made for the Case 6 experiment with the second ERV). The average indoor temperatures varied by 0.5^{o} C among the seven experiments, and the average RH varied by 4%. The standard deviation of the indoor RH also is shown (additionally see Moyer et al. (2004), Figure 3). The least variation was observed for Case 4, Dehumid, in which the dehumidifier was operated. The most variation was observed for Cases 6 and 7, ERV1 and Hstat, in which there were periods of elevated indoor humidity approaching or exceeding 60% RH. During the Case

2, Spot ventilation experiment, there were periods when indoor RH was below 40%. The average ambient RH was lowest during this period and many, but not all, of the low indoor RH values corresponded to low ambient values.

Indoor temperatures and RH during the active sampling collection periods presented in Table 2 were generally representative of the corresponding weekly average values. House air change rates measured by tracer gas decay during each active sampling period also are shown. With the exception of Case 2, Spot, values determined for these daytime periods are lower than values mostly determined for overnight periods when the wind conditions were calm relative to the day (Table 1).

For each experiment, the VOC concentrations measured by passive monitors in the main living area and the bedroom were averaged and the concentrations of any VOCs detected by the outdoor monitor were subtracted from the average indoor value. The indoor minus outdoor concentrations (termed adjusted concentrations) for five abundant VOCs measured by the OVM and formaldehyde measured by the aldehyde monitor are presented in Table 3. In this and subsequent tables, the target VOCs are listed first by chemical class (alcohols and esters, ketones, aldehydes, and aromatic and terpene hydrocarbons) and then in order of decreasing volatility within each class. The three aldehydes (formaldehyde, pentanal and hexanal) and the two terpene hydrocarbons (α-pinene and d-limonene) are emitted by composite wood products (Hodgson et al., 2003). The ester, 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate (TMPD-MIB) consisting of two isomers is emitted by latex paints (Hodgson, 1999). Average formaldehyde concentrations ranged from 27 to 46 $\mu g\ m^{-3}$. With the exception of formaldehyde, concentrations were lowest for Case 4, Dehumid, which had the highest overnight air change rate (i.e., 0.32 h^{-1}). With the exception of TMPD-MIB, concentrations were highest for Cases 1 or 2, None and Spot. The overnight air change rate was distinctly low for Case 1 (i.e., 0.15 h^{-1}) and relatively low for Case 2 (0.20 h^{-1}).

The VOC concentration and emission factor data determined by active sampling are summarized in Table 4. Listed are 17 of the most abundant VOCs determined by TD-GC/MS plus formaldehyde and acetaldehyde determined by HPLC. Measurement precision was obtained from sample pairs collected and analyzed by the same methods in a recent study of another manufactured house (Hodgson et al., 2004). Average indoor concentrations adjusted for any measured outdoor concentration were determined as described above for the passive sampler data. The median concentrations of six VOCs determined by active sampling can be compared to the corresponding medians of the data in Table 3. By passive sampling, the median concentrations of TMPD-MIB, hexanal, α-pinene and d-limonene were 22, 64, 100 and 8.6 μg m^{-3}, respectively. By active sampling, the median concentrations of these four compounds were substantially higher at 35, 146, 163 and 12.3 μg m^{-3}, respectively. On the other hand, the medians for formaldehyde and pentanal by the two methods were in good agreement, i.e., 36 and 22 μg m^{-3} by passive sampling versus 38 and 25 μg m^{-3} by active sampling. The causes of the differences between active and passive sampling results may be attributable to various factors, which were not investigated here. Potential factors include the large difference in the sampling duration (i.e., three hours versus 14 days), unknown differences in ventilation rates over these periods, and bias in the passive sampler data due to uncertainties in the effective sampling rates and the lack of correction for incomplete recovery of the analytes from the passive sampler.

The adjusted indoor VOC concentrations determined by active sampling for each ventilation case are presented in Table 5. For 13 of the 19 listed VOCs including formaldehyde, concentrations were lowest for Case 4, Dehumid, which had the highest air change rate (Table 2). For 13 of the 19 VOCs, concentrations were highest for Case 2, Spot, which had the lowest air change rate. The highest concentrations of the other six VOCs occurred for Case 1, None, with a relatively low air change rate. The ratios of the maximum to minimum concentrations for these VOCs are listed in Table 4. These ratios ranged from 1.7 for formaldehyde to 3.9 for phenol and toluene.

Emission factors derived from the adjusted concentrations and the air change rates for each ventilation case are presented in Table 6. For 16 of the 19 VOCs, emission factors were highest for Case 1, None. For eight of the 19 VOCs, emission factors were lowest for Case 4, Dehumd. These VOCs included acetaldehyde, C_5 to C_7 normal aldehydes, and all of the terpene hydrocarbons. The ratios of the maximum-to-minimum emission factors are listed in Table 4. These ratios ranged from 1.5 for 1-pentanol, 2-butanone, and hexanal to 5.7 for toluene. For all VOCs except toluene, there was less variation across the cases among emission factors than among adjusted concentrations.

Discussion

Only Cases 3, 4, 6 and 7 provided air change rates, as measured during active sampling, that approached or exceeded the new ASHRAE 62.2-2003 requirement for occupancy of this house by a family of four, i.e., 0.39 h^{-1}. None of the overnight air change measurements met this value.

The higher VOC emission factors for Case 1, None, may have occurred because the house was not operating at steady-state conditions at the time of sampling due to sporadic ventilation. Supply-based ventilation Cases 4 and 5 with the air handler fan controller supplying scheduled ventilation, Case 6 with the ERV in constant operation and Case 7 with the air handler fan operating at low speed for dehumidification likely provided the longest ventilation system run times and, thus, likely maintained more constant ventilation conditions than the other cases. When operating at near steady-state ventilation conditions, the emission factors of more volatile VOCs emitted by long-term sources, such as building products, are predicted to remain relatively constant. A study of another manufactured house, in which many of the same VOCs were measured, found that VOC emission factors at 0.31 h^{-1} air change were about 70 to 100% of the corresponding emission factors measured at 0.58 h^{-1} with approximately the same indoor temperature and RH conditions (Hodgson et al., 2004). Consequently, the indoor concentrations of VOCs emitted from these sources will be determined largely by the house air change rate. In fact, in this study, the emission factors of most of the VOCs did not vary substantially across Cases 4 through 7, and more broadly across Cases 2 through 7 (Table 6) with either exhaust- or supply-based ventilation. There was an approximate two-fold variation in ventilation rates for these six cases.

VOC concentrations determined by active sampling varied by about the same amount with the lowest concentrations generally occurring for Case 4, Dehumid (Table 5), when the house was operating at the highest air change of 0.44 h^{-1}, and the highest concentrations occurring for Case 2, Spot, when the house was operating at 0.20 h^{-1}. These trends were largely confirmed by the passive sampler results in which the lowest concentrations generally occurred for Case 4 and the highest concentrations occurred for the Cases 1 and 2 with relatively low air change rates.

The VOC concentrations in this house are generally consistent with values measured in other new manufactured houses (Hodgson et al., 2002, 2002 and 2004). The concentrations of hexanal and octanal exceeded their odor thresholds of 58 and 7 µg m^{-3} (Devos et al., 1990) in all seven ventilation cases. The nonanal odor threshold of 13 µg m^{-3} was exceeded in most cases. The lowest guideline for acceptable formaldehyde concentrations in residences has been 50 ppb (61 µg m^{-3}) (Sherman and Hodgson, 2004). Recently, the State of California has recommended a lower value of 27 ppb (33 µg m^{-3}) to avoid irritant effects (California Air Resources Board, 2004). Thus, the concentrations of a few VOCs in this house (and likely in many other new houses) are in the range of values that are of potential concern with respect to occupant comfort and health.

It is possible that some VOCs were partially removed from the air by the use of the dehumidifier. However, the dehumidifier accounted for just 13% of the total water removed by the dehumidifier and air conditioner combined (i.e., 67 of 520 kg for the period). Table 7 presents water solubilities for ten of the VOCs listed in Tables 5 and 6. Acetaldehyde has the highest solubility and the terpene hydrocarbons have the lowest solubilities. The emission factor of acetaldehyde was lowest for Case 4, Dehumid; however, a similar pattern was not observed for formaldehyde and 2-butanone, the other two relatively soluble VOCs. The issue was not investigated further.

Use of indoor humidity control in hot and humid climates is primarily to reduce incidences of moisture-related problems associated with mold growth. Humidity control may have the added benefit of limiting formaldehyde emissions from particleboard and other wood products produced with urea-formaldehyde resins. Matthews et al. (1986) developed an empirical model to describe the emission rate of formaldehyde from wood-derived products as a function of temperature, RH and ambient formaldehyde concentration. Silberstein et al. (1986) performed experiments with different wood products to validate the model in test chambers and a prototype house. The equations and parameters provided by Silberstein for particleboard were applied to the temperature, RH and formaldehyde concentration data for another manufactured house located in Gaithersburg, MD (Hodgson et al., 2004). The indoor RH values for the house ranged from 21 to 70% over the course of a year while the indoor temperature was relatively constant. Formaldehyde emission factors derived as described here ranged from 34 to 121 µg m^{-2} h^{-1} with the highest rates occurring in coincidence with the highest RHs. The factors predicted by the model were in reasonable agreement with the derived values strongly suggesting that indoor humidity has a substantial impact on formaldehyde emission factors and concentrations.

Conclusion

The study performed by Moyer et al. (2004) demonstrated that adequate ventilation could be provided with reasonable cooling/ventilation power usage for a house with simulated occupancy in a hot and humid climate. It was concluded that the key feature of the design for humidity control was the use of a correctly sized air conditioning system that allowed for extended system run times. It was concluded further that the addition of dehumidification provided the best interior humidity control with only a small increase in energy usage. In this portion of the study, we demonstrated that a house in a hot and humid climate that is designed for operation at a higher air change rate while still maintaining indoor RH near 50% is likely to have lower indoor concentrations of VOCs, including VOCs of concern, primarily due to the dilution effect. Additionally, we hypothesize that controlling indoor humidity to near 50% and below serves to limit formaldehyde emissions from wood products.

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Table 1. Average indoor and outdoor temperature and relative humidity (RH) conditions over 14 days for each of seven ventilation cases. House air change (ACH) rate values also are shown. Data are taken from Tables 1 and 2 and Figure 2, Moyer et al. (2004)

Parameter (Avg. Value)	Case 1 None	Case 2 Spot	Case 3 OA	Case 4 Dehumid	Case 5 10/20	Case 6 ERV1	Case 7 Hstat
Indoor Temp. (°C)	23.6	23.6	23.7	23.8	23.3	23.4	23.8
Indoor RH (%)	49	46	50	48	49	48	46
Indoor RH Std. Dev. (%)	1.47	1.27	1.67	0.84	1.23	2.19	3.07
Outdoor Temp. (°C)	25.9	25.9	25.8	27.8	26.6	26.3	26.2
Outdoor RH (%)	89	80	88	83	87	90	88
ACH (h^{-1})[a]	0.15	0.20	0.21	0.32	0.23	0.27	Nd[b]

a. Tracer gas decay measurements, mostly made overnight

b. Nd = no data available

Table 2. Average indoor and outdoor temperature, average indoor and outdoor relative humidity (RH), and house air change (ACH) rate for the active sampling event in each of seven ventilation cases

Case No./ Description	Avg. Temperature (°C) Indoor	Outdoor	Avg. RH (%) Indoor	Outdoor	ACH (h^{-1})
1, None	23.6	30.2	49	72	0.31
2, Spot	23.6	30.4	47	63	0.20
3, OA	23.8	29.5	53	77	0.36
4, Dehumid	23.9	31.6	50	66	0.44
5, 10/20	23.5	31.7	50	66	0.30
6, ERV1	23.5	28.8	50	82	0.36
7, Hstat	23.9	28.1	46	82	0.37

Table 3. Adjusted (indoor minus outdoor) concentrations of abundant VOCs measured by passive monitors during sampling intervals for each of seven ventilation conditions

	Adjusted Concentration (μg m^{-3})						
Parameter	Case 1 None	Case 2 Spot	Case 3 OA	Case 4 Dehumid	Case 5 10/20	Case 6 ERV1	Case 7 Hstat
TMPD-MIB[a]	26	24	47	18.7	22	21	21
Formaldehyde	46	44	39	30	35	36	27
Pentanal	38	43	28	12.9	21	19.3	22
Hexanal	90	106	71	35	62	49	64
α-Pinene	177	170	108	56	97	92	100
d-Limonene	16.0	14.1	10.9	5.5	7.6	6.9	8.6

a. TMPD-MIB = 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (combined isomers)

Table 4. Median adjusted (indoor minus outdoor) VOC concentrations and emission factors obtained for seven active sampling periods. Fractional variations in the ranges (maximum/minimum value) also are shown. Measurement precision is calculated from 10 sets of duplicate indoor samples from another house study (Hodgson et al., 2004)

Compound	Adj. Conc. (µg m^{-3}) Median	Adj. Conc. (µg m^{-3}) Max/Min	Emis. Fact. (µg m^{-2} h^{-1}) Median	Emis. Fact. (µg m^{-2} h^{-1}) Max/Min	Precision (%)
1-Pentanol	16.8	2.2	13.8	1.5	Nm[a]
Phenol	3.7	3.9	2.9	3.3	7
α-Terpineol	1.7	1.9	1.3	1.8	6
TMPD-MIB[b]	35	2.8	28	1.9	Nm
2-Butanone	34	2.1	25	1.5	18
Formaldehyde	38	1.7	28	1.6	Nm
Acetaldehyde	15.8	3.5	13.0	2.4	Nm
Pentanal	25	3.6	17.8	2.0	10
Hexanal	146	2.3	108	1.5	9
Heptanal	7.8	3.3	5.4	2.2	17
2-Heptenal (E-)	2.3	2.5	2.1	2.3	Nm
Octanal	14.0	3.0	9.7	2.1	14
2-Octenal (E-)	6.4	2.2	4.8	1.7	Nm
Nonanal	23.5	3.7	16.6	2.1	20
Toluene	5.2	3.9	5.3	5.7	40
α-Pinene	163	2.6	121	1.7	9
3-Carene	4.2	2.9	3.0	1.9	5
Camphene	2.3	3.1	1.8	2.1	6
d-Limonene	12.3	2.8	9.6	1.9	6

a. Nm = Not measured

b. TMPD-MIB = 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (combined isomers)

Table 5. Adjusted (indoor minus outdoor) VOC concentrations measured by active sampling over three hours on one day for each of seven ventilation conditions

	Adjusted Concentration (μg m^{-3})						
Compound	Case 1 None	Case 2 Spot	Case 3 OA	Case 4 Dehumid	Case 5 10/20	Case 6 ERV1	Case 7 Hstat
1-Pentanol	25	29	17.2	13.6	16.8	15.9	15.6
Phenol	7.6	3.4	3.7	2.6	4.2	5.4	1.9
α-Terpineol	2.8	2.6	2.6	1.5	1.7	1.6	1.4
TMPD-MIB[b]	41	59	21	33	39	35	30
2-Butanone	50	51	29	24	36	34	29
Formaldehyde	41	48	44	27	34	34	38
Acetaldehyde	29	28	15.7	8.4	18.6	12.6	15.8
Pentanal	42	52	25	15	25	20	21
Hexanal	210	230	146	99.1	156	127	135
Heptanal	13.0	13.4	8.5	4.1	7.8	5.7	6.0
2-Heptenal (E-)	5.2	5.2	4.0	2.1	2.3	2.1	2.1
Octanal	25	27	17.6	9.2	14.0	10.2	11.2
2-Octenal (E-)	5.7	10.1	4.6	6.4	6.9	6.3	6.6
Nonanal	28	43	24	14.0	24	14.4	11.6
Toluene	15.5	4.1	8.2	5.2	8.4	4.5	4.0
α-Pinene	240	260	133	99	164	153	163
3-Carene	6.6	7.0	4.2	2.5	4.3	3.4	3.3
Camphene	4.4	4.3	2.2	1.4	2.3	2.1	2.5
d-Limonene	22	21	12.7	7.8	12.3	9.7	11.3

a. TMPD-MIB = 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (combined isomers)

Table 6. VOC emission factors derived from active sampling measurements made in each of seven ventilation cases

	Emission Factor ($\mu g\ m^{-2}\ h^{-1}$)						
Compound	Case 1 None	Case 2 Spot	Case 3 OA	Case 4 Dehumid	Case 5 10/20	Case 6 ERV1	Case 7 Hstat
1-Pentanol	17.8	13.8	14.2	13.8	11.6	13.2	13.3
Phenol	5.4	1.6	3.1	2.7	2.9	4.5	1.6
α-Terpineol	2.8	2.6	2.6	1.5	1.7	1.6	1.4
TMPD-MIB[b]	29	28	17.7	33	27	29	26
2-Butanone	35	24	24	25	25	28	25
Formaldehyde	29	22	37	28	23	28	32
Acetaldehyde	21	13.4	13.0	8.5	12.8	10.4	13.4
Pentanal	30	25	21	14.9	17.5	16.3	17.8
Hexanal	152	107	121	101	108	105	114
Heptanal	9.2	6.3	7.0	4.2	5.4	4.8	5.1
2-Heptenal (E-)	3.7	2.5	3.3	2.1	1.6	1.8	1.8
Octanal	17.5	12.8	14.5	9.3	9.7	8.5	9.5
2-Octenal (E-)	4.0	4.8	3.8	6.5	4.8	5.2	5.6
Nonanal	20	20	19.4	14.2	16.6	11.9	9.8
Toluene	11.0	1.9	6.8	5.3	5.8	3.7	3.4
α-Pinene	168	121	110	101	114	127	139
3-Carene	4.7	3.3	3.5	2.5	3.0	2.8	2.8
Camphene	3.1	2.0	1.8	1.5	1.6	1.8	2.1
d-Limonene	15.4	9.9	10.5	8.0	8.5	8.0	9.6

a. TMPD-MIB = 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (combined isomers)

Table 7. Water solubilities of selected VOCs. Data were obtained from the Hazardous Substances Data Bank (HSDB®, 2004)

Compound	Solubility (g L^{-1})	Temperature (^oC)
1-Pentanol	27	22
Phenol	83	25
2-Butanone	353	10
Formaldehyde	400	20
Acetaldehyde	1,000	25
Pentanal	11.7	20
Hexanal	6	20
Toluene	0.53	25
α-Pinene	Insol	
d-Limonene	0.014	25