Measured Cooling Season Results Relating the Impact of Mechanical Ventilation on Energy, Comfort, and Indoor Air Quality in Humid Climates

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ABSTRACT

In Florida, residential whole house mechanical ventilation is not required by code and market penetration of ASHRAE 62.2 compliant mechanical ventilation systems is poor. There is concern amongst regional builders and contractors around implications of mechanically introducing humid outside air compared to the indoor air quality benefits, which many feel are not adequately documented or demonstrated. These implications include impact on energy use, comfort, durability, and cost. This paper describes results from a study in Gainesville, FL relating the impact of ventilation on these parameters.

Ten homes built and occupied in the 2009-2010 timeframe with HERS Index < 65 have been under evaluation since June 2013. All ten homes were built with a central fan integrated supply ventilation system (CFIS) delivering an average of 35 cubic feet per minute (cfm) of outside air during heating/cooling operation only, and average 3.6 ACH50. As part of this study, a bathroom exhaust fan in each home was replaced with a larger capacity fan capable of exhausting a continuous 60 cfm on average, approximating ASHRAE 62.2-2010 requirements. The homes were divided into two cohorts: 6 homes that alternate between the CFIS ventilation system and the continuous exhaust ventilation system every 2 weeks, and 4 homes that operate one of the ventilation systems exclusively (2 homes per system). Monitoring of temperature, relative humidity, CO_2 concentration, and space conditioning energy use occurs continuously, while concentrations of formaldehyde, acetaldehyde, TVOC, and NO_2 are measured seasonally. Results spanning late June through mid-October 2013 are presented and discussed.

Introduction

Whole building air exchange is an important element to maintain healthy indoor air quality (IAQ) in residential buildings. Air exchange acts to dilute indoor air pollutants with fresh, outdoor air. Other components that make up a comprehensive strategy for IAQ include limiting materials and activities providing the source of pollutants, and employing local exhaust in dedicated areas where high concentrations of contaminants are likely to occur (i.e. kitchens).

Several residential codes and standards require whole building mechanical ventilation in addition to natural air exchange (Martin 2013). The various differences among these requirements, along with the lack of mechanical ventilation requirements in many state and local codes, indicate that there is some uncertainty regarding the appropriate level of ventilation in different geographic or climate regions. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE)'s standard 62.2, "Ventilation and Indoor Air Quality in Low-Rise Buildings," is the most commonly referenced residential ventilation standard in the United States. The 2010 version of ASHRAE 62.2 (ASHRAE 62.2-2010) is currently required by ENERGY STAR Version 3, the 2012 International Energy Conservation Code, U.S.

Department of Energy's (DOE's) Zero Energy Ready Home Criteria, many state Weatherization programs, and other home performance programs. The 2013 version of the standard was published during the course of this study.

In practice, effective IAQ is often judged by perceptions of comfort, odor and moisture control, which has little to do with occupant health. There is concern amongst builders and contractors in hot humid climate regions over the implications associated with mechanically introducing large volumes of humid outside air, compared to the perceived IAQ benefits, which many feel are not fully documented or demonstrated. These implications include the potential impact on IAQ, energy use, comfort, durability, and both first and operating costs. Previous research suggests that formaldehyde, a common indoor air pollutant, may actually act as a constant concentration pollution source, with emission rate increasing in response to greater outdoor air exchange (Weisel et al. 2005, Willem et al. 2013).

To balance factors related to comfort, energy use, and odor and moisture control, some builders of high-performance homes in the hot humid climate have utilized a supply based whole-house mechanical ventilation strategy linked to runtime of the central heating, ventilation, and air-conditioning (HVAC) system – often termed "central fan integrated supply (CFIS)" (Chandra et al. 2008, Rudd and Lstiburek 2008). This system has been employed since the mid 1990's and has been implemented in thousands of homes. Based on a number of implementation related factors, outdoor air flow rates induced by the central system fan, and hence ventilation air volumes, have varied between 15 and 100 percent of ASHRAE 62.2-2010 required rates for continuous fan flow. Due to energy and comfort concerns, rather than delivering the outdoor air continuously, many builders have opted to only deliver mechanical ventilation during heating and cooling operation – termed "runtime vent (RTV)". This report describes a field study in which data are being collected to evaluate the impact of differing ventilation rates on energy use, comfort, and indoor air contaminant concentrations.

Materials and Methods

Concentrations of indoor air contaminants, ventilation system airflow rates, space conditioning energy use, indoor temperature and relative humidity (RH) are measured in 10 high performance homes in Gainesville, Florida that operate with two different ventilation strategies: 1) the RTV system originally delivered with the homes, delivering approximately 20% of ASHRAE 62.2-2010 requirements annually, and averaging 35 cubic feet per minute (cfm) during heating/cooling operation; and 2) a continuous exhaust ventilation (CEV) approach that approximates ASHRAE 62.2-2010 requirements for whole house mechanical ventilation, averaging 60 cfm. To achieve the target continuous exhaust flow, a bathroom exhaust fan in each home was replaced with a larger capacity fan. Six of the 10 homes are flip-flopped between the two ventilation strategies every two weeks. Two of the homes remain in the RTV configuration (configuration 1) throughout the study period. The last two homes remain in the CEV configuration (configuration 2) throughout the study period.

The homes were all newly occupied in the 2009–2010 timeframe, are in the same subdivision, have similar specifications, and were built to the DOE's Builders Challenge 1.0 guidelines with Home Energy Rating System (HERS) Indicies < 65. Most of the homes are single story, slab-on-grade, with ductwork located in vented attics.[1] The HVAC systems in these homes are single-stage heat pumps with seasonal energy efficiency rating (SEER) 15 or 16. The

[1] One home has a bonus room on a second floor, and one home has ducts inside the conditioned space.

systems have no provisions for enhanced humidity control outside of their standard latent capacity. Additional characteristics of the homes are listed in Table 1.

Table 1. Characteristics of the study homes

House	cohort	Area (sqft)	Bedrooms	Occupants (adults / children)	ACH50	Qn, out (cfm25 / 100 sqft)	RTV flow (cfm)	Exhaust Fan Flow (cfm)	62.2-2010 / 2013 fan req. (cfm)
1	Flip-flop	2158	5	2 / 2	5.1	3.4	40	57	67 / 71
2	Flip-flop	1508	3	2 / 2	4.4	0	34	55	45 / 52
3	CEV control	1542	3	1 / 2	3.0	2.2	N/A	54	45 / 60
4	Flip-flop	1984	4	2 / 0	3.4	3.0	26	55	57 / 73
5	CEV control	1950	4	2 / 2	3.0	1.6	N/A	59	57 / 75
6	Flip-flop	1679	3	2 / 0	3.5	1.8	42	55	47 / 60
7	RTV control	1878	4	2 / 3	3.4	1.0	35	N/A	56/ 71
8	Flip-flop	1508	3	1 / 1	2.9	1.5	39	78	45 / 60
9	Flip-flop	1542	3	3 / 0	4.8	2.0	24	64	45 / 50
10	RTV control	2416	4	2 / 1	2.6	4.6	37	N/A	62 / 87
	Flip-flop average	1730	3.5	2.0 / 0.8	.4.0	2.1	34	61	51 / 61
	Control average	1947	3.8	1.8 / 2.0	33.0	2.4	36	57	55 / 73
	Overall average	1817	3.6	1.9 / 1.3	33.6	2.2	35	60	53 / 66

Table 2 lists the various measurement parameters, measurement equipment, and sampling rates for the environmental, energy, and IAQ metrics evaluated in this study.

Table 2. Data collection details[2]

Measurement	Equipment Used	Sampling/Storage Interval
Total Energy (Wh)	eMonitor (current transducer [CT])	hourly
Air Handler Energy (Wh)	eMonitor (CT)	hourly
Condenser Energy (Wh)	eMonitor (CT)	hourly
Bath Fan Circuit Power (Wh)	eMonitor (CT) or U-12 HOBO (CT)	hourly
Space T & RH (4 interior locations)	(1) Extech[(a)] T/RH/CO_2, (3) U-10 HOBOs	15 min
Ambient T & RH	Extech T/RH/CO_2	15 min
Infiltration (CFM 50)	Blower Door	Initial baseline
Runtime vent flow (cfm)	Exhaust Fan Flow Meter	Initial baseline
Exhaust fan flow (cfm)	Exhaust Fan Flow Meter / Powered flow hood	Initial baseline
Interior CO_2 (ppm)	Extech CO_2/T/RH	15 min
Ambient CO_2 (ppm)	Extech CO_2/T/RH	15 min
Formaldehyde (ppb)	Passive sorbent badge[(b)]	Weekly, 4 events/year
Acetaldehyde (ppb)	Passive sorbent badge[(b)]	Weekly, 4 events/year
Volatile Organic Compounds (ppb)	Passive sorbent badge[(b)]	Weekly, 4 events/year
Nitrous Oxides/ Nitrogen Dioxide (ppb)	Passive sorbent badge[(b)]	Weekly, 4 events/year

(a) The Extech device uses infrared technology to measure CO_2.
(b) Passive IAQ samplers are mailed to a laboratory for analysis. Analysis is performed using standard EPA protocols for the identification of volatile organics (TO-17) and formaldehyde/acetaldehyde (TO-11A).

[2] The air exchange rate in the homes is also being measured with perfluorocarbon tracer (PFT) during each IAQ sampling event, with weekly averaging. Results will be analyzed at a later date.

The IAQ contaminants of concern in this study were chosen to sufficiently characterize the IAQ in residential homes in Florida. The indoor air pollutants most commonly associated with building materials and building-related activities are formaldehyde and volatile organic compounds (VOCs) (Dales et al. 2008). A recent meta-analysis by LBNL identified 15 pollutants as chronic hazards in more than 50 percent of homes studied and 9 as priority pollutants in U.S. homes (Logue et al. 2010). The constituents of concern identified for this study are total and speciated volatile organic compounds, formaldehyde and acetaldehyde, and nitrous dioxide (NO_2).[3]

Results are presented from the first sampling period in the summer of 2013 spanning June 28 through October 15. Subsequent sampling periods are planned for winter and a duplicate summer period in 2014.

Results and Discussion

Continuously Monitored Parameters (Energy Use, Temperature, Relative Humidity, Dew Point, and Carbon Dioxide)

Figure 1 characterizes the weather conditions in Gainesville, FL during the summer monitoring period, and shows the periods of runtime vent operation ("RTV" in the figure) and continuous exhaust ("CEV" in the figure) operation in the flip-flop homes. Average daily outdoor dry bulb temperature is shown along with average hourly outdoor dew point temperature. Both parameters remain relatively constant throughout the first half of the summer period, and among flip-flop configurations, with a peak occurring around August 20. After this peak, ambient temperature begins to trend downward, and the dew point becomes more variable.

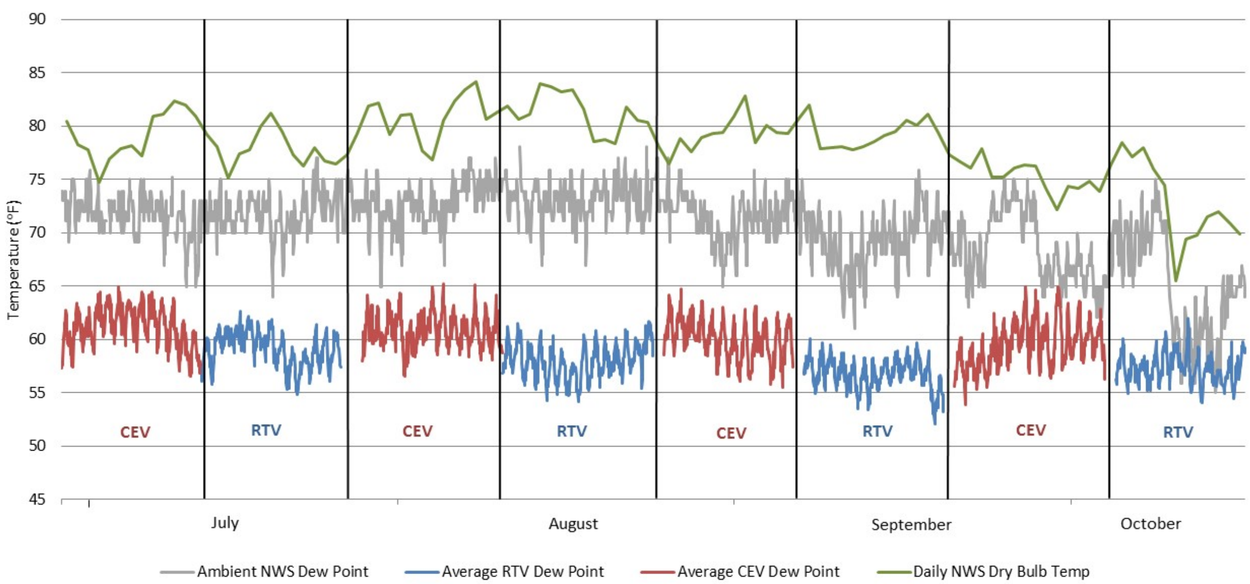

Figure 1. Outdoor dry bulb and dew point temperatures from the local National Weather Service (NWS) station are shown along with average indoor dew point temperature for the six flip-flop homes. Red indicates continuous exhaust (CEV in the figure) configuration and blue indicates the run time vent (RTV in the figure) configuration.

[3] Measurements of radon and particulates, and visual evidence of mold and mildew, are also being recorded and will be analyzed at a later date.

Figure 1 also shows indoor dew point temperatures, which in general, show lower moisture content inside the homes than that seen outdoors. This is because the air conditioning system removes much of the moisture introduced through both air exchange and internal generation. While indoor dew point can be seen as influenced by outdoor dry bulb temperature driving runtime of the air conditioner, an overall trend is apparent showing a lower average indoor dew point temperature during runtime vent than during continuous exhaust.

Figure 2 shows the number of hours during the summer period each of the homes spent in specific RH ranges: < 60%, 60-65%, and > 65%, broken into the two ventilation periods. Also displayed are average interior temperatures. Total number of hours varies since logistics prevent the flip-flop homes from all being switched over on the same day. Data has also been removed from this plot and all subsequent analysis representing extended vacation periods (sites 5 and 6) and air conditioner failures/repairs (sites 1 and 10). In the Figure, control home data has also been broken into two periods representing the average date ranges the flip-flop homes spent in each ventilation configuration. In general, the hours > 60% for the control homes are two times greater in the continuous exhaust (right bar) periods than in the runtime vent periods (left bar). The increase largely occurs in the hours between 60-65% RH, and could be explained by slight differences in average outdoor dew point between the periods. The flip-flop homes log significantly more hours > 60% RH during the continuous exhaust periods as compared to the runtime vent periods, including in hours > 65% RH.

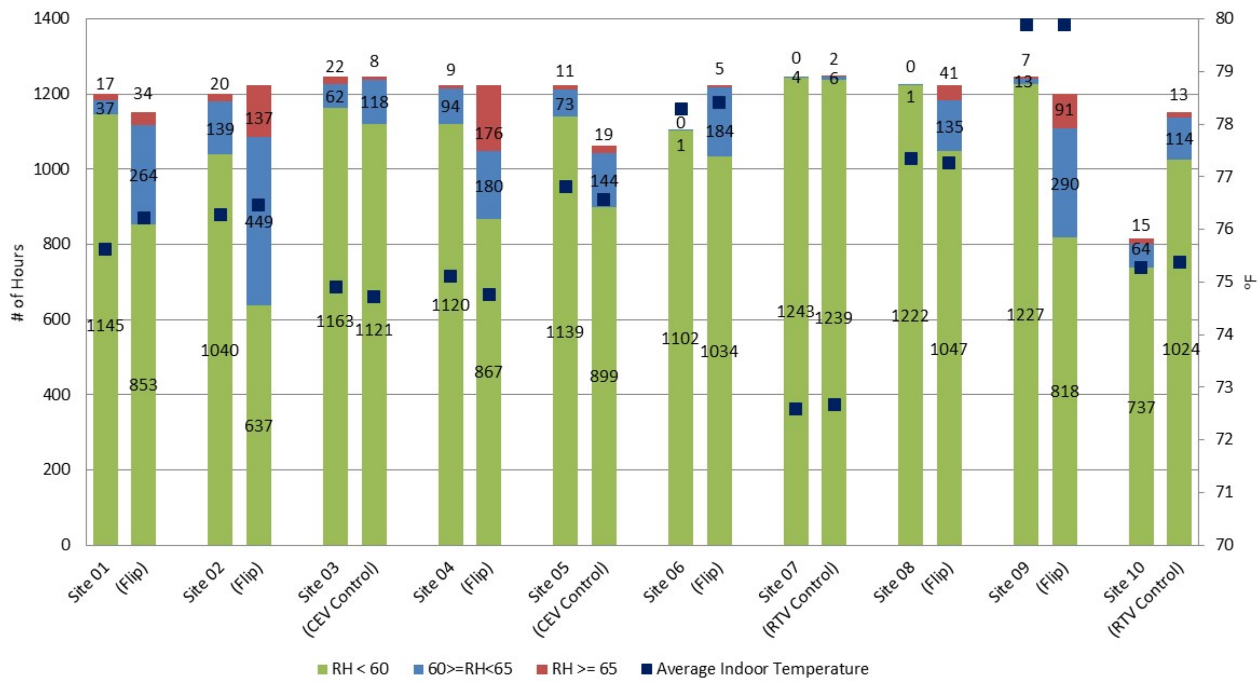

Figure 2. Distribution of hours at various % RH ranges, broken into runtime vent (left bar) and continuous exhaust (right bar) periods, each corresponding to the left axis. Numeric data labels correspond to hours, black squares correspond to average indoor temperature (on the right axis). Sites 3 and 5 always operate with continuous exhaust, and sites 7 and 10 always operate with runtime vent.

Figure 3 shows the average daily HVAC energy use per day for each of the homes, broken into the different ventilation periods. This energy use includes both the air handler fan and the compressor, but does not include bathroom exhaust fan energy for the continuous exhaust condition. With the exception of site 10, whose trend is unexplained, the control homes show little variation in HVAC energy use among the periods. The flip-flop homes however show greater HVAC energy use during the continuous exhaust period indicating, as expected, that the additional ventilation is placing additional load on the air conditioner.

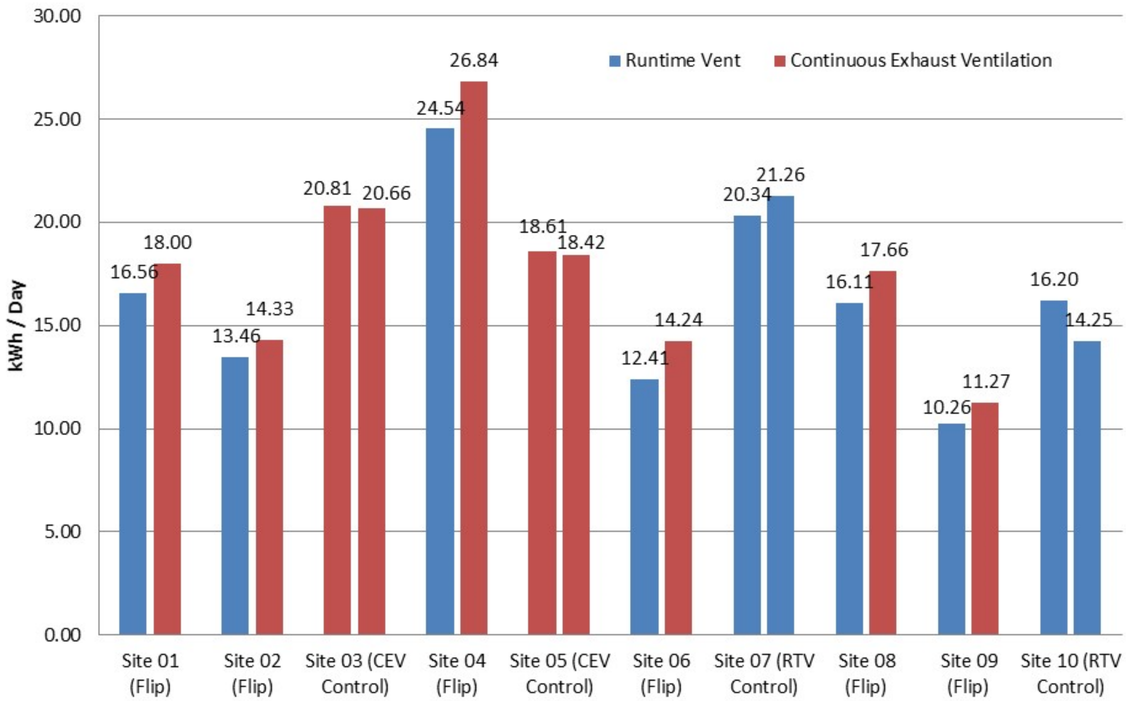

Figure 3. Average HVAC energy use per day, broken into runtime vent (left bar) and continuous exhaust (right bar) periods. Sites 3 and 5 always operate with continuous exhaust, and sites 7 and 10 always operate with runtime vent.

There is no correlation between minor differences in average indoor temperature between the periods in a given home (black squares in Figure 2) and differences in average space conditioning energy between the periods in a given home. However, thermostat set point is a driver behind differences in space conditioning energy use among homes. In order to remove the influence of differing indoor and outdoor temperatures from the comparison of HVAC energy between the two ventilation strategies, Figure 4 plots average daily cooling energy vs. average daily outdoor and indoor temperature difference for the six flip-flop homes. Similar analysis has been used in the past to compare performance of various highly efficient homes to conventional counterparts (Chasar et al. 2006). In this plot, each data point represents a single day. The x-axis coordinate is the difference between average outdoor temperature for the day, and the average indoor temperature averaged for all 6 flip-flop homes for that day. The y-axis coordinate is the total cooling energy use averaged for all 6 homes for that day. Assuming the area under each line is directly proportional to cooling energy use, the flip-flop homes use approximately 9% more cooling energy while operating under continuous exhaust ventilation, over the delta T range of -4 to 6 ^{o}F.

The general trend for the continuous exhaust configuration to result in greater HVAC energy use and slightly higher dew point temperatures is seen in Figure 5, which displays a representative average day profile for the flip-flop homes operating under the two ventilation

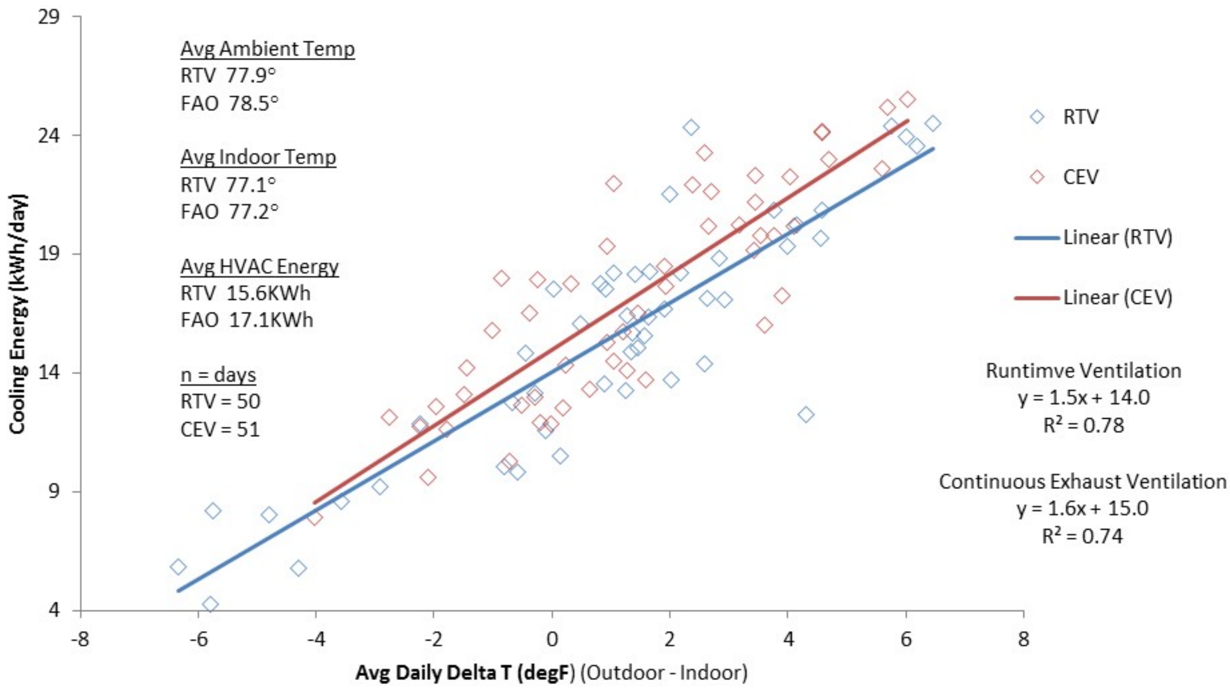

Figure 4. HVAC energy use as a function of differences in indoor and outdoor temperatures.

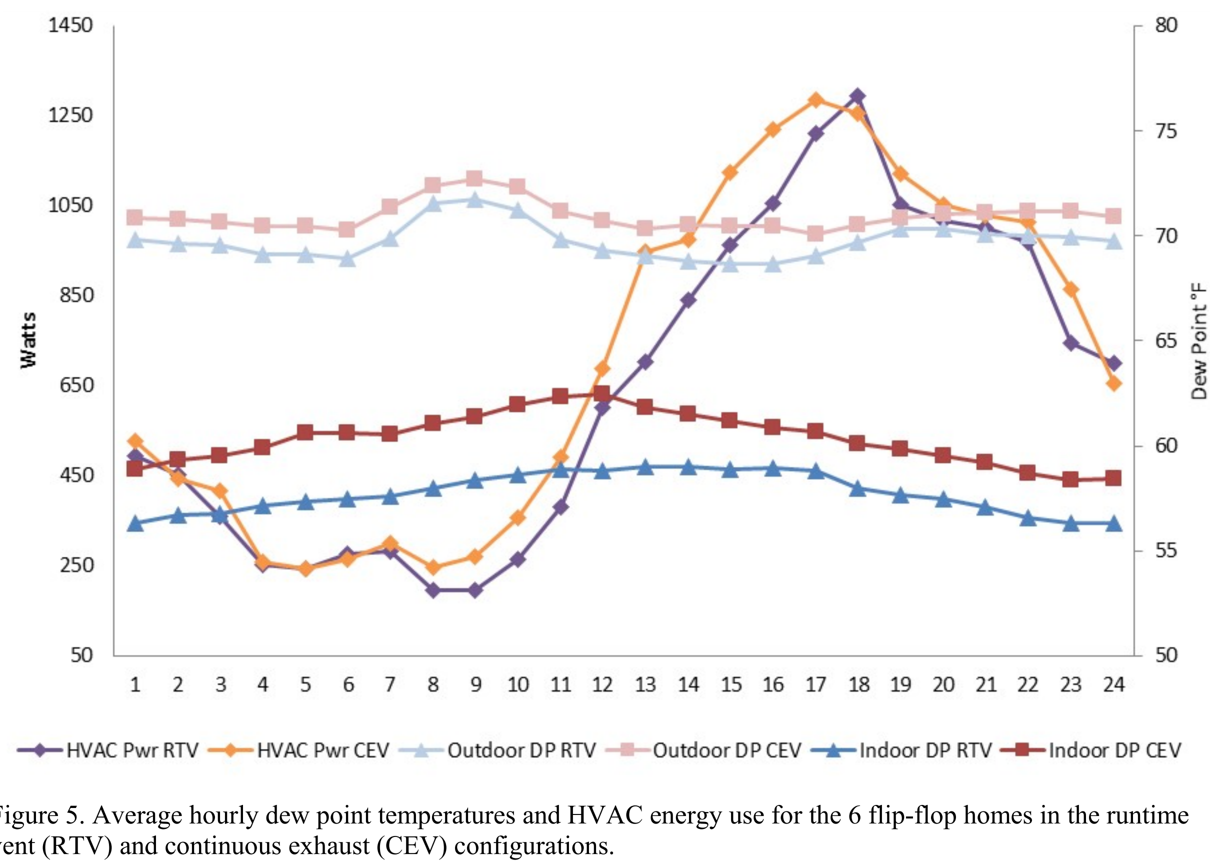

Figure 5. Average hourly dew point temperatures and HVAC energy use for the 6 flip-flop homes in the runtime vent (RTV) and continuous exhaust (CEV) configurations.

configurations. This plot is generated by averaging hourly data for all 6 flip-flop homes while in each of the two configurations. Much of the difference in HVAC energy occurs during the daytime hours, when temperatures are at their warmest, with little difference in peak demand. The gap in average indoor dew point temperature widens slightly in the early morning hours as HVAC runtime is reduced. Around 12:00pm, after a few hours of increased HVAC runtime, the gap in average indoor dew point temperature narrows.

Figure 6 shows daily average CO_2 concentrations for all homes, for the period of 8/15/2013 – 10/15/2013. It is clear that CO_2 concentration is reduced in the flip-flop homes when operating with continuous exhaust. With the exception of Site 10, the control homes also show a reduction in CO_2 concentration during the continuous exhaust period, despite the outdoor concentration remaining nearly constant, which is unexplained. The difference could be related to occupancy, which is not tracked in detail. It could also be related to the accuracy of the Extech SD 800 CO_2 sensor, which has an accuracy of +/- 40 ppm[4]. However, the reduction in CO_2 concentration in the flip-flop homes is 2 times greater on average than the reduction in CO_2 in the control homes during the same periods, which indicates the additional ventilation provided via the continuous exhaust system is likely producing a dilution effect.

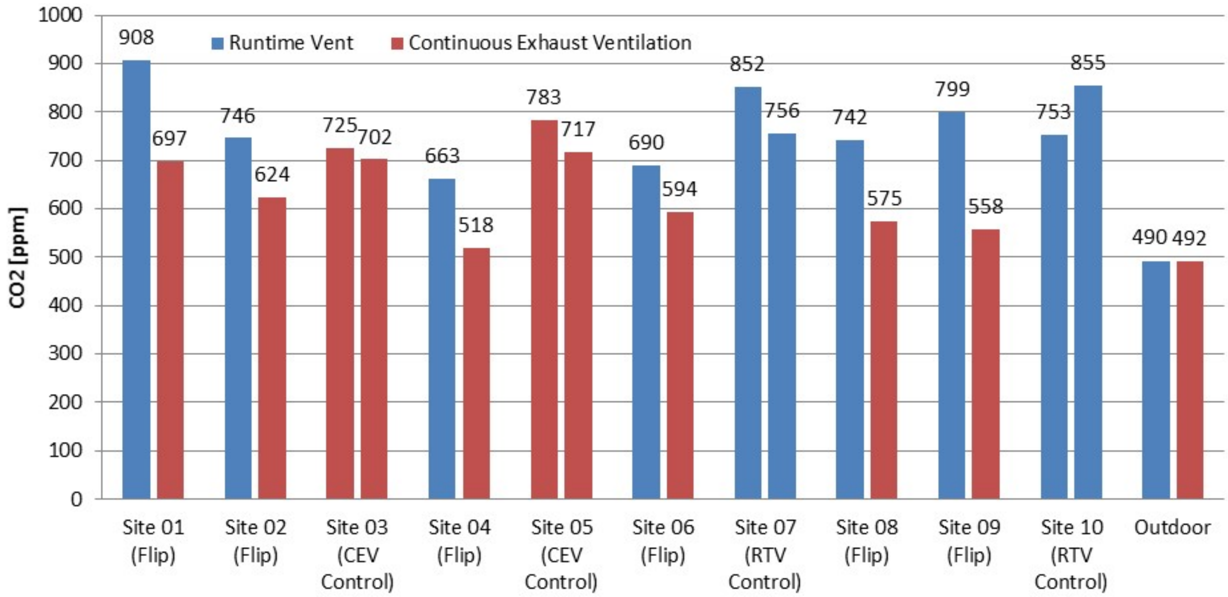

Figure 6. Daily average CO_2 concentration, broken into runtime vent (left bar) and continuous exhaust (right bar) periods. Sites 3 and 5 always operate with continuous exhaust, and sites 7 and 10 always operate with runtime vent.

Table 2 summarizes the monitored data collected over the summer period for the 6 flip-flop homes. Outdoor conditions were relatively consistent throughout. As expected, the continuous exhaust ventilation system approximating ASHRAE 62.2-2010 levels of ventilation requires slightly more space conditioning energy use to maintain the desired temperature set points in the homes. As these homes have no mechanism to control RH, resulting RH and dew point is higher in the homes while under continuous exhaust ventilation.

[4] The CO_2 sensors recorded short periods of indoor CO_2 concentration well below outdoor values, which is unexplained. For the purposes of this discussion, any recorded CO_2 concentrations below 400 ppm were excluded from analysis.

Table 2. Summary of monitored data over the summer period, averaged for the 6 flip-flop homes.

	Continuous Exhaust	Runtime Vent	Δ
Indoor Temp (°F)	77.2	77.1	0.1
Indoor RH (%)	56.5	51.6	5.1
Indoor Dew Point (°F)	60.4	57.8	2.6
Hours 60-65% RH	250	48	202
Hours > 65% RH	80	9	71
AC Energy (kWh/day)	17.1	15.6	1.5
Indoor CO_2 concentration (ppm)	594	758	-164
Outdoor Temp (°F)	78.5	77.9	0.6
Outdoor RH (%)	79.4	78.3	1.1
Outdoor Dew Point (°F)	70.9	69.8	1.1
Outdoor CO_2 concentration (ppm)	492	490	2

Seasonally Sampled Parameters (Formaldehyde, Acetaldehyde, Volatile Organic Compounds, and Nitrogen Dioxide)

Formaldehyde. Formaldehyde levels in all of the homes were higher than the National Institute for Occupational Safety and Health (NIOSH) recommended chronic exposure limit of 16 ppb (CDC 2011) and are consistent with average concentrations measured in other newly constructed U.S. homes (Salthammer, Mentese, and Marutzky. 2010). The NIOSH-recommended exposure limit is based on the fact that formaldehyde is a known carcinogen and a philosophy that exposure to carcinogenic compounds should be limited to below the limit of detection (CDC 2011). The Occupational Safety and Health Administration (OSHA) permissible exposure level for chronic exposures is much higher at 750 ppb. However, this limit is designed primarily for work environments where 8-hr exposures are typical while people are often in their homes significantly more than 8 hours per day.

In general, no clear trend was observed relating relative formaldehyde concentrations to ventilation strategy or ventilation rate. In two of the flip-flop homes, homes 1 and 8, formaldehyde levels were observed to be higher with continuous exhaust ventilation than in the runtime vent case, as shown in Figure 7. The reverse trend (decreased formaldehyde concentrations with continuous exhaust ventilation compared to runtime vent) was observed in house 6. Homes 2 and 4 exhibited an insignificant change between the runtime vent and continuous exhaust sample periods. The runtime vent sample in house 9 appears to be an outlier, potentially due to deployment issues, and thus data from house 9 is removed from the analysis.

Formaldehyde levels were nearly constant in the control homes that are always under continuous exhaust (homes 3 and 5) and one of the control homes that remains in the runtime vent condition (home 7). In addition, formaldehyde levels were higher in homes 3 and 5 than in home 7. However, home 10 exhibits unusual behavior, with very high concentrations measured during the first summer sampling period and much lower concentrations measured during the second sampling period. It is hypothesized that this may be due to the introduction of new furnishings or a large, cleaning event that led to the unusually high concentrations. This hypothesis is currently being investigated, but all average data is reported with the data from home 10 removed.

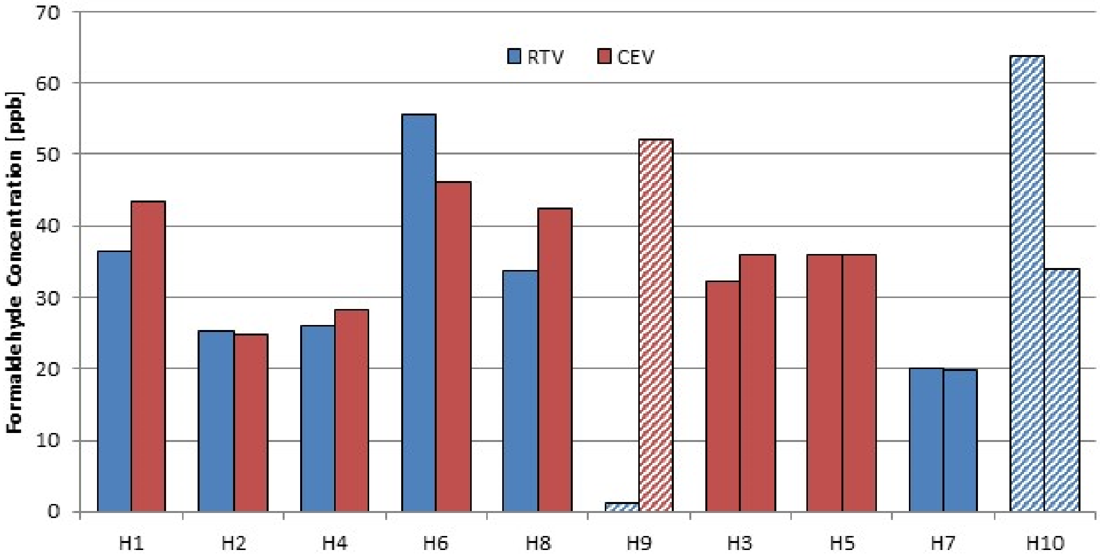

Figure 7. Concentrations of formaldehyde in homes 1 through 10 during the two paired summer IAQ sample periods, where blue represents home in the runtime vent configuration ("RTV" in the figure) and red represents homes in the continuous exhaust configuration ("CEV" in the figure). Dashed bars indicate homes that have been removed from subsequent analysis.

On average, the concentration of formaldehyde in the homes with continuous exhaust ventilation was higher (35 ppb) than in the homes with runtime vent (31 ppb),[5] although the difference is not significant. The data do not demonstrate a clear relationship between increased levels of ventilation and formaldehyde concentrations, likely due to the difference in ventilation strategies. The RTV system is an intermittent supply-only approach, while the CEV system is a continuous exhaust ventilation system. While the differences may confound analysis of formaldehyde concentrations with respect to ventilation rate, effectiveness, or approach (supply vs. exhaust) independently, comparison of RTV and CEV is representative of the changes to ventilation strategies that could be implemented in the field to meet ASHRAE 62.2 requirements.

These preliminary data suggest that increased ventilation provided via an exhaust fan does not consistently reduce concentrations of formaldehyde in the indoor environment and may even result in increased formaldehyde concentrations in some homes. It is hypothesized that this may be due to depressurization that pulls make up air through cracks in the building envelope, which may pull in additional formaldehyde if the building envelope is constructed with materials containing formaldehyde, or from items stored in attached garages. Subsequent data collection periods are necessary to better characterize formaldehyde concentrations when moving from a runtime vent strategy to a continuous exhaust ventilation strategy in the hot humid climate.

Acetaldehyde. Acetaldehyde was sampled in all of the homes and outdoors. In general, concentrations of acetaldehyde measured in these homes were very low, ranging from 3 to 13 ppb during the first sampling period and 2 to 9 during the second sampling period. The average concentration of acetaldehyde measured in the flip-flop homes decreased from the first IAQ sampling period to the second, or from the runtime ventilation condition to the continuous

[5] Note this removes the outlier concentrations from house 9 and 10. If houses 9 and 10 are included, the average formaldehyde concentrations are 37 ppb and 32 ppb for the CEV and RTV ventilation cases, respectively. If only house 10 is included and house 9 is excluded, the average concentration is 35 ppb for both ventilation cases.

exhaust condition, however, the reduction between the two sampling periods and ventilation conditions was slight and was not significant based on only this paired sampling period.

Acetaldehyde standard levels vary among organizations, based on the data used to inform the standards and the acceptable degree of risk based on the circumstances the standard is designed for (EPA 2012). The OSHA limit, designed to protect workers in industrial environments, is 200 ppm (OSHA 2006) while the American Industrial Hygiene Association sets an Emergency Response Planning Guideline Level 1 limit of 10 ppm, which is meant to represent the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing other than mild transient health effects or perceiving a clearly defined, objectionable odor (AIHA 2013). In either case, the acetaldehyde concentrations measured in these homes are far below any published standard limits.

Volatile organic compounds. TVOC concentrations were observed to increase from the first sampling period to the second sampling period in all cases, including the control homes, as shown in Figure 8. As with formaldehyde, house 10 exhibited the highest measured concentration of VOCs by a wide margin and is removed from the analysis. Although increased concentrations of TVOCs were also observed in the other homes that were not modified between the two sampling periods (houses 3, 5, and 7), TVOC levels increased 98 percent in the flip-flop homes compared to an average increase of 76 percent in the control homes. The fact that, on average, the average increase in TVOC concentration increased more in the flip-flop homes than in the control homes indicates that there may be a relationship between TVOCs and moving from runtime vent to a continuous exhaust ventilation strategy, where increased levels of exhaust ventilation in fact increases concentrations of TVOCs indoors relative to outdoor concentrations. The research team hypothesizes that this relationship may be due to the exhaust-only ventilation method employed causing air to be pulled through the building envelope and, thus, increasing emission of VOCs into the environment. Further data collection and analysis is required to verify and better understand this theory.

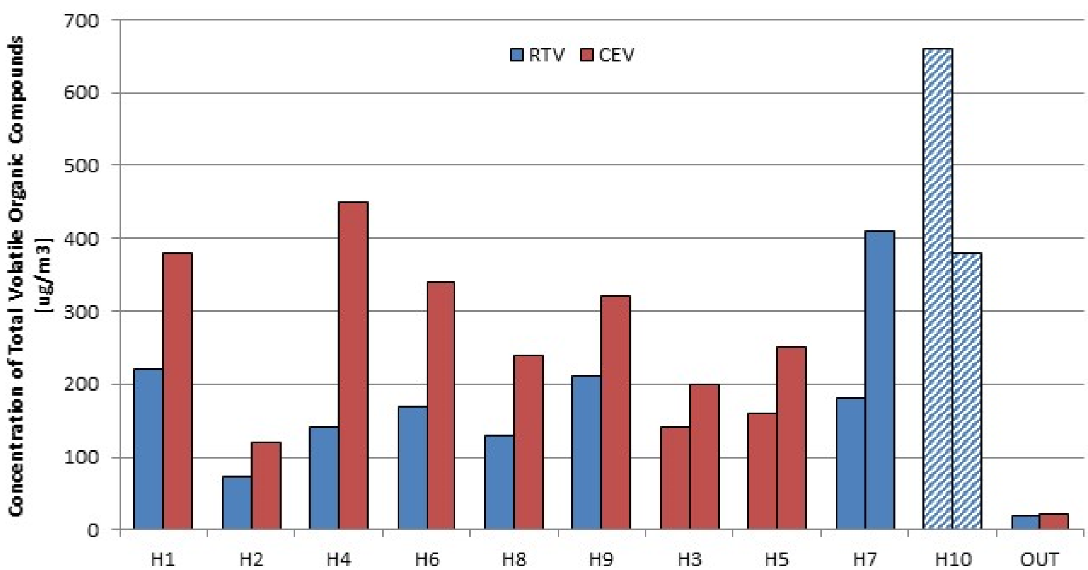

Figure 8. Concentration of TVOC in homes 1 - 10 during the two paired summer IAQ sample periods, where blue represents the runtime ventilation configuration (“RTV”) and red represents the continuous exhaust (“CEV”). Dashed bars indicate homes that have been removed from analysis.

As the health effects caused by different VOCs varies greatly from those that are highly toxic, to those with no known health effect, increased levels of various VOCs may or may not result in negative health effects. In general, VOCs tend to cause or contribute to eye, nose, and throat irritation; headaches, loss of coordination, nausea; damage to liver, kidney, and central nervous system. Some VOCs are likely or known carcinogens (EPA 2012).

Figure 9 depicts the most commonly occurring VOCs in the first and second sampling periods[6] which are acetone, ethanol, ethyl acetate, isopropyl alcohol, methyl ethyl ketone, and methylene chloride. In general, a wider variety of VOCs were observed in the second sampling period with, in general, lower concentrations than observed in the first sample period. Most of the observed VOCs are all solvents and, at the low levels observed in these homes, not known to have negative health effects. The research team continues to investigate the likely cause of each of the commonly occurring VOCs, to help understand why an inverse relationship with ventilation rate may be observed. Although, higher levels of VOCs with exhaust ventilation versus supply ventilation have been observed in previous studies (Rudd and Bergey, 2013). In addition, data collection during subsequent IAQ sampling will demonstrate whether this suite of VOCs continues to be observed throughout the year or if the suite of VOCs changes seasonally.

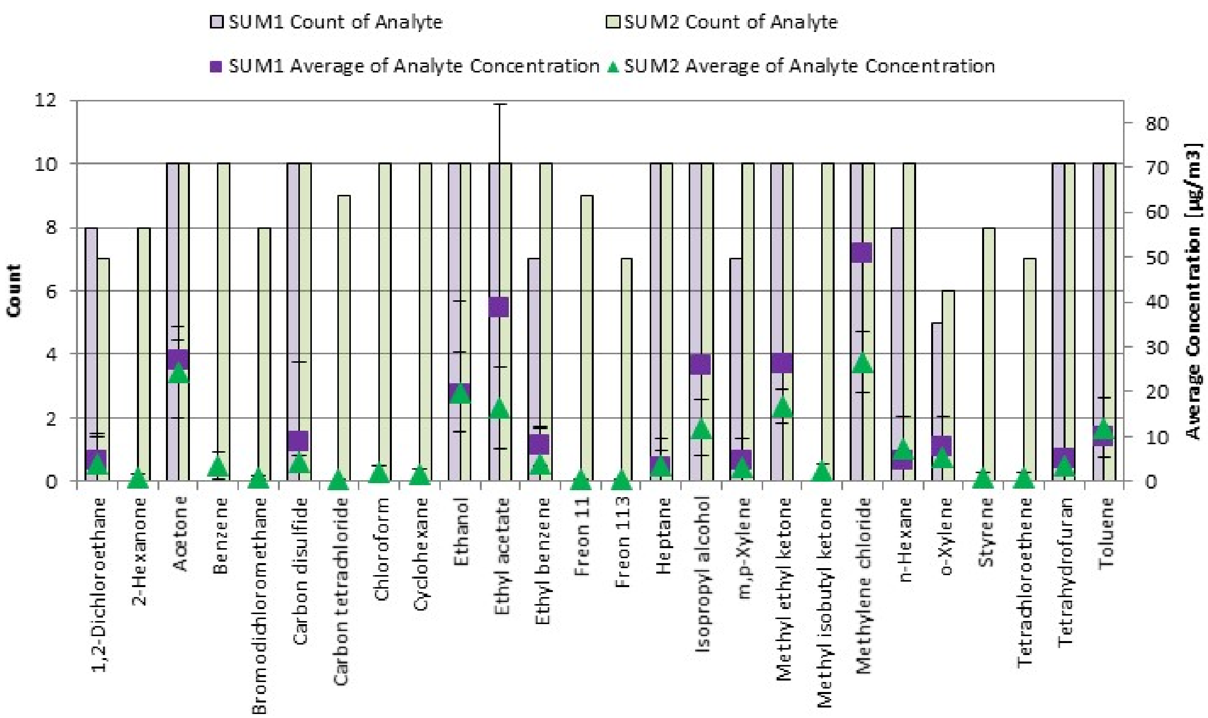

Figure 9. Average concentration and frequency of occurrence for most commonly observed VOCs from first (SUM1; purple) and second (SUM2; green) IAQ analysis periods.

Nitrogen dixoide. NO_2 was sampled only in one home with gas cooking equipment and one home without, as well as outside. NO_2 exhibited a more predicable trend with respect to

[6] VOCs that occur in greater than 5 homes are depicted. In general, VOCs were common among homes; only trichloroethane, dibromochloromethane, 4-ehtyl toluene, and 1,2,4-trimethylbenzene were observed in less than 5 homes in the second sampling period and no compounds were observed in less than 5 homes in the first sampling period.

ventilation rate, decreasing from 3 to 1 ppb with increased ventilation during the continuous exhaust periods. The data also show that increased levels of ventilation led to approximately 50 percent lower concentrations of NO_2 in the homes with gas, while a reduction of approximately 30% was observed in the homes without gas between the runtime ventilation and continuous exhaust ventilation conditions. The concentrations of NO_2 were also observed to be higher in the home with gas cooking (3 ppb) than in the home without gas cooking (1ppb) and also exceeded outdoor levels of NO_2 (2ppb) in the home with gas cooking in the runtime vent configuration. However, the NO_2 concentration outdoors during the second sampling period was below the sensitivity limit of the sampler, which makes the data difficult to compare between the first and second summer sampling periods.

While a decrease in concentrations of NO_2 is beneficial, as it illustrates a dilution of cooking-related contaminants resulting from the whole-house ventilation, no standards have been agreed upon for nitrogen oxides in indoor air and the concentrations measured here are an order of magnitude lower than the EPA's National Ambient Air Quality Standard for NO_2 in outdoor air of 53 ppb averaged over a 24 hour period. Subsequent data collection periods of indoor and outdoor NO_2 concentrations are necessary to better characterize the relationship between NO_2 concentrations and whole-house ventilation observed here.

Conclusions

Concentrations of indoor air contaminants, ventilation system flow rates, space conditioning energy consumption, indoor temperature, and indoor relative humidity were measured in ten high performance new homes in Gainesville, Florida, along with corresponding outdoor conditions, to characterize the impact of differing ventilation rates on these parameters. Continuous exhaust ventilation, with rates approximating that required by ASHRAE 62.2-2010, was compared to intermittent runtime ventilation, delivering approximately 20% of ASHRAE 62.2-2010 requirements annually. As expected, the continuous exhaust ventilation systems result in approximately 9% more space conditioning energy use on average to maintain the desired temperature set points in the homes during the June 28-October 15 2013 sampling period. As these homes have no equipment for enhanced humidity control, resulting RH and dew point are higher in the homes while under continuous exhaust.

Concentrations formaldehyde, acetaldehyde, VOCs, and NO_2, were determined in two paired sampling periods during the summer of 2013. Preliminary analyses of the data indicate that concentrations of acetaldehyde and nitrogen dioxide have predictable responses to increased ventilation, exhibiting decreased concentrations with increased ventilation rate. In addition, these contaminants are far below published standard levels and are not likely to cause negative health effects at these low levels.

Concentrations of formaldehyde and VOCs, however, were not observed to be reduced with increased ventilation rates from continuous exhaust ventilation. In general, the relationship between formaldehyde and VOCs was variable among homes. However, in some cases, concentrations of VOCs and formaldehyde increased significantly from the runtime ventilation condition to the continuous exhaust condition in the flip-flop homes. It is hypothesized that this may be a result of the exhaust-only ventilation method pulling make-up air through the building envelope and increasing emission rates of any solvents or other volatile chemicals contained in the materials used to construct the envelope, such as insulation or wall board, or materials stored in attached garages. However, further data collection and analysis are necessary to verify these trends and confirm this hypothesis. While the most commonly observed VOCs are primarily ubiquitous solvents and the measured concentrations are all well below published standard limits, this is not the case for formaldehyde, a known carcinogen. Formaldehyde concentrations were, on average, 35 ppb in the homes with continuous exhaust ventilation and 31 ppb in the homes with runtime ventilation, while the NIOSH-recommended exposure limit is 16 ppb. Concentrations in all of the homes were above the NIOSH-recommended exposure limit.

In all cases, additional data is needed to verify the significance of these findings and ensure the observed trends are continued. Collecting a full year of monitored data, along with subsequent IAQ sampling in winter and spring, and pairing this data with measured air exchange rates obtained from PFT, is in process.

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