A Field Study of Ventilation System Effectiveness in Low Air Leakage Residences

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ABSTRACT

This paper reports on the results of a field study of five different ventilation system types in 29 homes in the Pacific Northwest. The homes studied ranged in air-tightness from just over three air changes per hour at 50 Pascals to less than one. Carbon dioxide, relative humidity and temperature were monitored in multiple rooms in both the heating and shoulder seasons while residents performed week long experiments with bedroom doors open or closed and ventilation systems on or off. Residents were asked to keep journals of these actions and use of auxiliary fans, and bedroom door closures and ventilation fan status were also monitored. In addition the paper reports the results of one-day tracer gas decay tests done on 26 of these homes. The paper compares the measured effectiveness of the five types of ventilation systems in terms of removing site-generated CO_2 and tracer gas. It also assesses the impact of house tightness on ventilation performance and the fan electricity invested in providing ventilation. Resident knowledge of their ventilation systems, maintenance of systems and as-found control setting impact on ventilation effectiveness are also reported.

Introduction

Since the adoption of the 1991 Washington State Ventilation and Indoor Air quality Code and subsequent revisions, Washington State has been a leader in the use of residential whole house ventilation systems (Lubliner et al. 2002). Since 1991 more than 800,000 dedicated whole house ventilation systems have been installed in new homes in the state. New homes have gotten progressively tighter driven by code requirements and performance expectations. With tighter and tighter homes, concern has grown as to the overall effectiveness of the predominant ventilation systems being installed.

This study reports on a Washington State University (WSU) Energy Program research project commissioned and funded by the Northwest Energy Efficiency Alliance (NEEA). Field research was conducted on 29 homes in the Pacific Northwest. A complete cycle of tests was completed in each house first during colder winter conditions and then repeated in the milder spring conditions of 2013. Analysis of seasonal effects has not been completed and is not reported here. The test sites represent the top tier of house tightness in a sample of homes built in the region after 2006. Air leakage ranged from just over three air changes per hour at 50 Pascals (ACH_{50}) to less than one (roughly 0.15 ACH to 0.015 ACH natural). Five different types of ventilation systems representative of the most commonly used systems in the region were tested in a range of home tightness configurations. The ventilation systems studied were:

1. **Exhaust Only**
2. **Exhaust – Trickle**: exhaust only with window or trickle vents
3. **CFA Integrated**: ventilation integrated with central forced air

4. **HRV and ERV**: heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs) ducted systems with supplies in bedrooms and main living areas, returns in bathrooms and kitchens
5. **CFA Int.-HRV**: ERV/HRV integrated with central forced air

Five research questions were considered:

1. Characterization of estimated direct electrical energy use by the ventilation system,
2. The relative effectiveness of the ventilation system types,
3. Factors that contribute to ventilation effectiveness,
4. The degree to which ventilation systems reduce CO_2 levels during normal occupancy and use, and
5. House occupant knowledge and satisfaction.

Pre-screening of the homes determined that all of the ventilation systems were capable of being operated to meet the requirements of the ASHRAE standard 62.2 2010 during the experimental period.

The analysis of the long-term data set presented in this report focuses on a small portion of the data set: the master bedroom at night during the four test weeks. Future analysis will examine the main living area and second bedroom, incorporating additional data into the analysis, considering other variables, and focusing on certain sets of houses.

House & Ventilation System Characterization

The study focused on ventilation system performance. Each home was extensively characterized including occupancy levels and patterns, blower door testing, duct leakage to the exterior testing as appropriate, ventilation system flow measurements, flow measurements of all exhaust appliances, amperage draws for all ventilation fans, and system-induced pressure differentials between house and exterior and between interior zones. Exhaust only and HRV systems made up the largest share of the ventilation systems. For the complete characterization of all the homes see the Phase 1 Project report (WSU 2013). Table 1 summarizes the basic characteristics of the homes. Homes labeled E# were located in the colder International Energy Conservation Code (IECC) climate zone 5 east of the Cascade Mountains. Homes labeled W# were located in the milder marine climate zone 4 west of the Cascades.

Table 1. House characteristics

Site #	Ventilation System Type	ACH_{50}	Year Built	Area	Floors	Occupants	Bedrooms	Baths
E01	Exhaust Only	1.94	2011	1,656	1	2	3	2
E03	HRV	0.89	2012	1,876	2	2	2	2
E05	Exhaust - Trickle	3.18	2010	1,310	2	4	3	1
E09	CFA Int.	3.2	2008	2,843	2	3	3	3
E10	HRV	2	2011	1,896	1	2	1	2
E11	Exhaust Only	2.76	2012	2,364	2	4	4	3
E13	Exhaust Only	1.82	2011	1,352	1	1	2	2

Site #	Ventilation System Type	ACH_{50}	Year Built	Area	Floors	Occupants	Bedrooms	Baths
E16	CFA Int.	2.39	2009	2,805	2	2	3	2.5
E18	Exhaust Only	1.44	2009	3,150	2	2	3	2
E19	CFA Int. - ERV	3.1	2012	1,700	2	1	3	2.5
E22	ERV	0.36	2011	2,115	2	2	2	2.5
E23	CFA Int. - ERV	3.1	2010	2,843	1	2	3	3.5
E25	HRV	1.08	2012	1,496	1	2	3	2
E26	Exhaust - Trickle	3.5	2011	1,199	1	2	3	2
W02	HRV	1.02	2011	3,675	3	7	4	4
W04	HRV	2.65	2012	3,024	2	2	3	2.5
W06	HRV	1.42	2011	1,881	2	3	3	3
W07	Exhaust - Trickle	2.93	2012	2,080	2	2	3	3
W08	Exhaust - Trickle	3.31	2012	1,080	1	6	3	1
W12	HRV	0.57	2011	1,904	2	4	3	3
W14	Exhaust Only	2.6	2004	3,300	2	4	3	3
W15	Exhaust - Trickle	2.3	2012	1,176	1	2	3	2
W17	Exhaust Only	2.11	2012	1,240	2	2	3	3
W20	HRV	1.94	2012	1,832	2	4	3	2
W21	Exhaust Only	2.26	2008	1,971	2	2	3	2
W24	Exhaust Only	0.71	2011	1,900	2	2	3	2
W27	Exhaust - Trickle	2.87	2012	1,216	2	3	3	2
W28	Unique	0.29	2011	1,970	1	4	4	2
W29	Exhaust Only	0.26	2012	1,764	2	2	3	2

Data Collection

Data was collected in short-term and long-term field experiments using a standard set of test conditions (ventilation systems on and off, bedroom doors open or closed). Data collected included:

- CO_2, temperature, and humidity measurements in the main living area and two bedrooms,
- Bedroom door closure status,
- Ventilation system fan operation,
- A journal maintained by occupants, and
- Outdoor temperature and humidity.

Long term data measurements were made at 15-minute intervals. Short term measurements were made at 1-minute intervals

Experimental Design

The analyzed data came from two sets of field experiments—a set of long-term experiments conducted over many weeks by homeowners and a set of short-term (partial-day) experiments conducted by WSU Energy Program field staff.

Long Term

Experiments were conducted with ventilation systems on and off, doors open and closed, and trickle vents open and closed for those homes with trickle vents. Table 2 shows the combination of test conditions used for each test week in the study and the naming convention used to report the results. Note that houses with trickle vents had twice as many test weeks so that tests could be conducted with trickle vents opened or closed. The long-term test consisted of two phases: heating season and shoulder season in which the entire experimental protocol was repeated.

Table 2. Test week status conditions

Test Week	A	B	C	D
Ventilation System	On	On	Off	Off
Bedroom Doors	Open	Closed	Open	Closed
Trickle Vents	Open or Closed	Open or Closed	Open or Closed	Open or Closed

At each test site, the home occupants were asked to keep a journal that recorded:

- The start and end dates of each week-long experiment in the long-term study,
- Status of ventilation system during the experiment,
- Status of doors during each test week,
- Reading of CO_2 level at the beginning of each test,
- Minutes that exhaust appliances (other than the ventilation system) were used each day, as estimated by the home owner and
- Comments on each experiment and day, if any.

The WSU Energy Program field staff met with the home occupants and assessed their knowledge of the ventilation system in their home and mastery of the system controls and settings.

Short-Term Field Study

The short-term field study required that the WSU Energy Program field staff spend six to eight hours at each test site. Houses were unoccupied during testing. Tests were done from mid-April to mid-June for 26 of the houses. CO_2 readings were taken with highly accurate WMA-4 CO_2 analyzers from PP Systems.

The test protocols paralleled the test structure of the long-term tests—with ventilation system on and off, doors opened and closed, and trickle vents open and closed. However, for the short-terms tests, a known amount of CO_2 was injected into the house air, mixed evenly, and the decay was measured (following ASHRAE Method of Test E-741-11). Data was collected for each site containing one minute carbon dioxide concentration logs for three primary zones in each house: main living area, master bedroom and secondary bedroom. To eliminate CO_2 emissions the homes were not occupied (including researchers) during decay periods and there was no combustion occurring. The field researchers kept a journal during the test that documented experimental conditions including exterior temperature and the exact time and sequence of tests.

Results

The analysis of the data was an iterative process that involved organizing it into data sets, examining the data quality, analyzing and making comparisons of ventilation effectiveness for particular houses and across houses, and further refining the analysis to provide additional insights and address issues found in the analysis. Details of the analytic methodology are contained in the project analysis report (Eklund et al. 2013).

Estimated Ventilation Fan Energy Use

Fan run time and power measurements were used to estimate the annual electric energy use from operating different types of ventilation systems. All measurements were taken in alternating current (AC) prior to any conversion to direct current (DC). The control settings were recorded, and the actual run times were measured in most cases. Power factor was not measured on site. For purposes of this analysis, the power factor was assumed to be 0.8, based on a review of manufacturers' specifications. **It was not the intent of this phase of the research to estimate the space conditioning energy use impacts of the various ventilation systems.** Instead, the direct energy use of the ventilation system components and the air flows produced were measured, from which a more comprehensive estimate of total energy use might be developed later. The direct energy use of the ventilation systems by system type is in Table 3.

Table 3. Estimated electricity use per year by ventilation system type

System Type	Count	Average (kWh)	High (kWh)	Low (kWh)	Standard Deviation (kWh)
Exhaust w/w-out Trickle Vents	15	163	547	34	139
HRV/ERV	11	504	765	202	196
Integrated with CFA	3	1,072	1,564	515	431
All	29	386	1,564	34	351

Note: The system type categories shown in this table for the energy analysis vary slightly from the categories shown in Table 1 that were used in the performance analysis.

Relative Effectiveness of Ventilation Systems Studied

"Effectiveness" is the ability of the ventilation systems to remove or dilute pollutants and provide fresh air for occupants. This long term study primarily focused on the ability to remove or dilute CO_2 rather than the sources and quantity of fresh air. To compare the effectiveness of the systems studied, the performance metric of measured CO_2 levels in the houses during different test conditions was evaluated. The test condition status and the different types of ventilation systems were the primary variables considered.

Data from the long-term and short-term studies provided insight for this analysis. Each study followed a different approach:

- The long-term study measured the impact of key variables on natural CO2 levels, such as ventilation system on or off with bedroom doors open or closed and window (trickle) vents open or closed.
- The short-term study used CO2 as a tracer gas, introduced a known quantity, and observed its decay over a period of time while deploying the same key variables.

Short-term study results. The short-term study measured decay rates of known concentrations of CO_2 for 26 of the test homes using very accurate monitors while changing key factors such as ventilation system "on" status, bedroom door status, and window vent status. Ventilation air changes per hour were calculated from the decay rates. The same questions were posed for the short-term study as for the long-term study, but the answers are given in the calculated air changes produced by the ventilation systems under various conditions. The algorithm for this calculation was provided by Terry Brennan (T. Brennan, Principal, Camroden Assoc., Inc., pers. Comm., April 16, 2013)

To most accurately represent the ACH of multiple individual zones would require a unique tracer for each zone, which was not done in this study. Having only one tracer gas in multiple zones when doors are closed ignores the possible interaction between zones and differences in tracer concentrations that develop. In this analysis, the absolute ACH in different rooms is not the key focus—instead it is the relative performance of different types of ventilation systems under the same set of typical occupancy conditions.

The tests with the ventilation system off provide a baseline for this analysis of ventilation system performance. For the main living area, the mean ACH values were 0.07 to 0.08; for the master bedroom, the mean ACH values were 0.05 to 0.06. The value was below 0.10 ACH for most of the houses, less than 1/3 of generally recommended levels. These levels clearly demonstrate the need for ventilation in homes with low air leakage.

Figure 1 shows the calculated air changes per hour as determined from the measured CO_2 tracer decays for the master bedroom when the ventilation system is on and the door is open or closed. When the door is open, all three system types perform similarly. The median values range from 0.28 to 0.36 ACH. Closing the door causes virtually no change in the CFA integrated median ACH value, but there is almost a 25% drop in the exhaust only median value and a 47% increase in the HRV median effective ACH. However, the range of ACH values for the HRV systems increases significantly, indicating that some of the individual systems had a much greater change in performance than others under this test condition. The specific location of HRV returns and supplies and the location of exhaust only fans relative to bedrooms and open air pathways probably affect these values and are under further analysis.

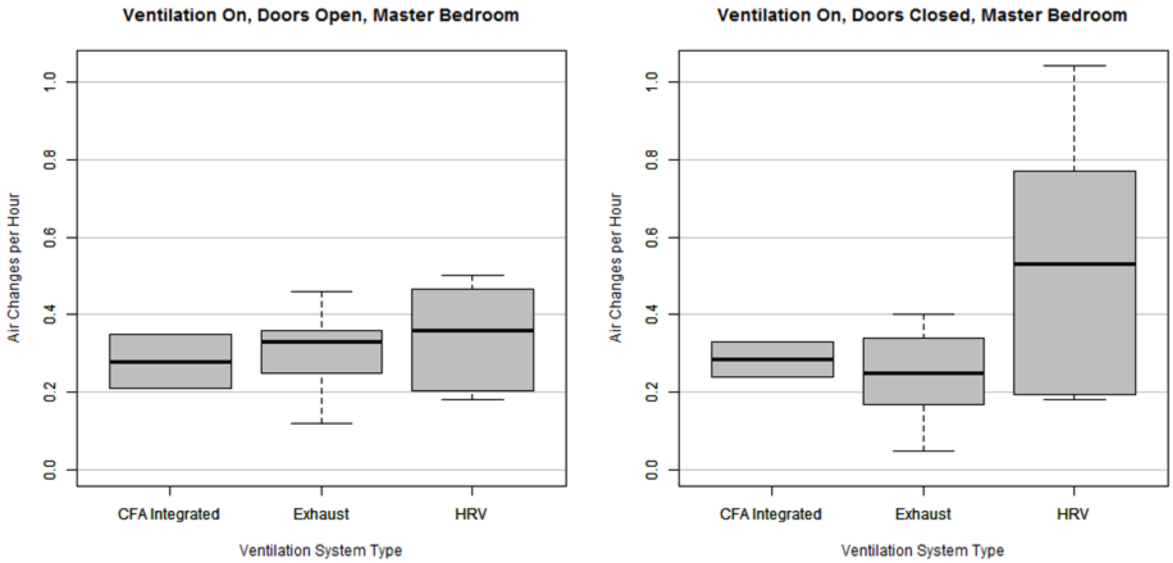

Figure 1. Master bedroom test ACH with ventilation system on and doors open or closed.

This is the most dramatic condition shown by the short-term test. Under conditions where the highest production of natural CO_2 takes place (at night in the master bedroom with the doors closed), the ability of exhaust only systems as a group decreased while the average performance of HRVs improved. CFA integrated ventilation function was stable, but still below 0.3 ACH.

Conversely, in the main living area there was very little difference in the test ACH values for the different ventilation systems or for the door open or closed conditions (Figure 2). All of the systems had ACH values around 0.3 with the doors open. For exhaust only systems located in the main living area, there is minimal difference in the median ACH value with the doors closed or open because the path from the main living room to the exhaust fan is not affected by closing the doors. There is a small drop in the ACH values for the CFA integrated and HRV systems because the flow paths are affected by closing the doors. For the HRV systems, the median ACH value goes up significantly in the master bedroom when the doors are closed but declines slightly in the main living room, suggesting that with the doors closed, there is likely reduced flow back to the main living space indicating that these systems are not perfectly balanced.

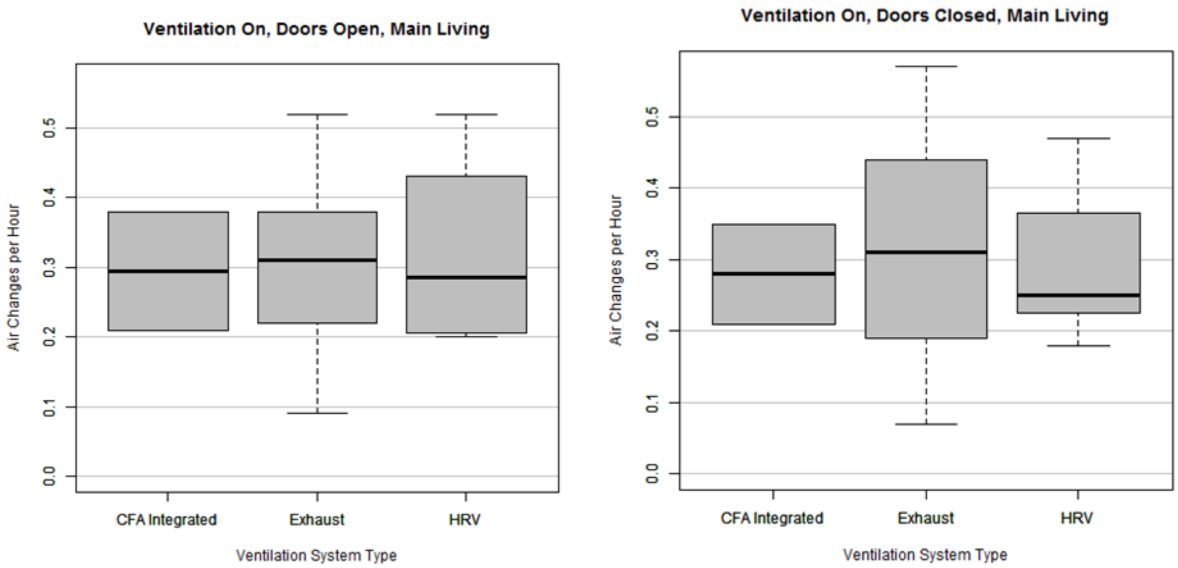

Figure 2. Main living area test ACH with ventilation system on and doors open or closed.

Exhaust only with trickle vents is the other ventilation strategy reported here. In the short-term tests and analysis, the WSU Energy Program team compared the performance of these systems with the vents open and closed for the six houses with trickle vents. Figure 3 shows the results of this comparison for the master bedroom. Note that when the bedroom doors are open, there is very little difference in the average performance with vents open or vents closed. When the doors are closed, the vents appear to make a difference. The median air change rate increases from 0.25 to 0.35, or 43%. There was an increase in air change rate for all six houses but it is still insufficient to bring the median ventilation level to a rate consistent with reducing CO_2 to 1,000 ppm or less with assumed emission rates for sedentary occupants.

When the same experiment is performed in the main living area, the results are inconsistent. With doors open, opening the vents cause the median effective ACH to increase, but there is a lot of variation and in some of the houses the ACH decreases when the vents are opened. The results are reversed when the doors are closed – there is a little more ventilation on average with vents closed than open. However, the variation in ACH is large --in some houses it increases and in others it decreases. The trickle vents have little consistent impact on the ACH in the main living area.

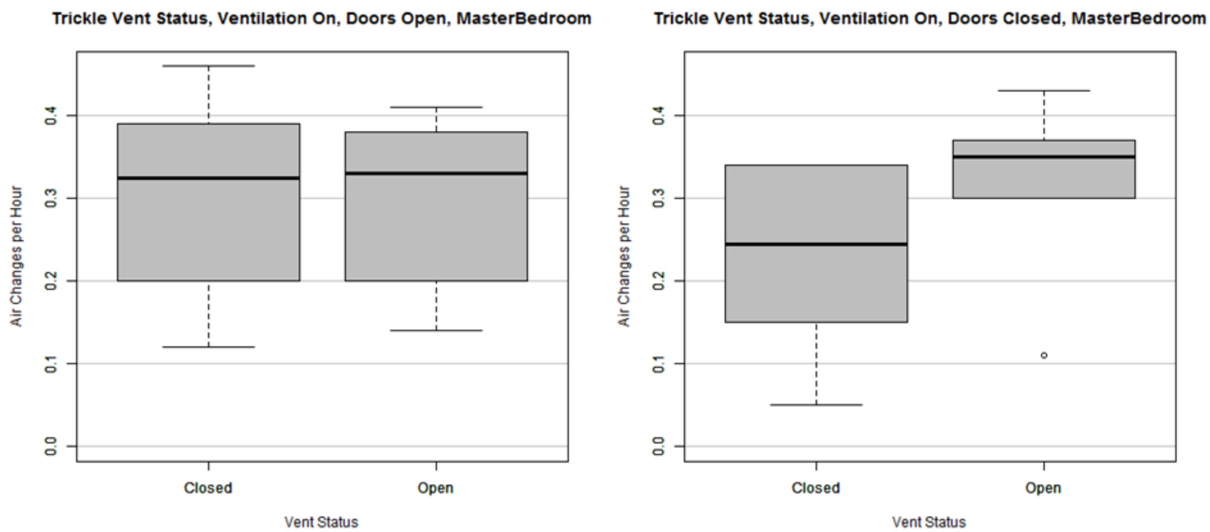

Figure 3. Impact of trickle vents open or closed on master bedroom test ACH.

Long-term study results. To follow the long-term study data analysis, it is critical to understand the cycle of test weeks when each test site participated (see Table 2). The preliminary analysis of long-term study data focused on the master bedroom between midnight and 6 a.m., when it is likely to be occupied and the need for ventilation is the most significant. It is under these conditions where the differences between the ventilation systems would be most apparent. This is illustrated in Figure 4, which shows all the measured CO_2 data for the master bedroom for house #E01 a home with exhaust only ventilation centrally located in the laundry. The highest CO_2 levels tended to occur during the early morning hours. Levels tended to be lowest with the ventilation system on and doors open (test A), increased when the doors were closed (test B), increased more with the ventilation system off and doors open (test C), and were highest when the ventilation system was off and doors closed (test D).

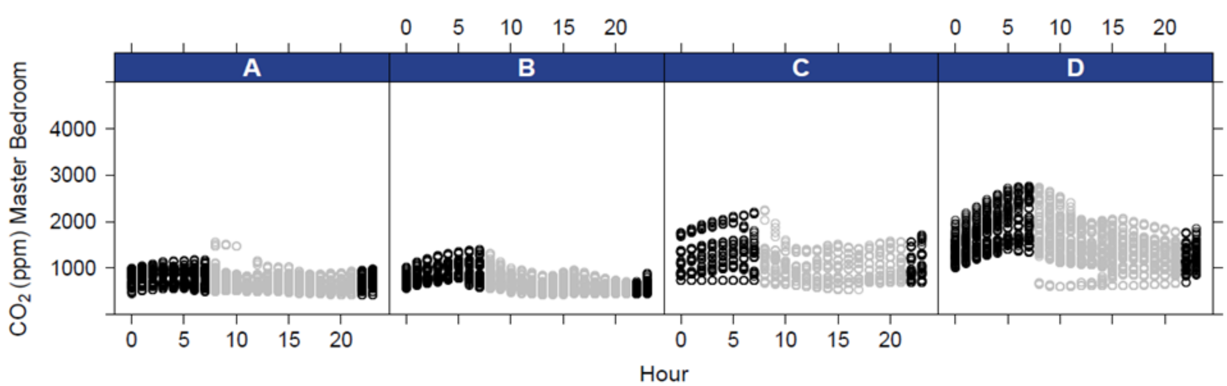

Figure 4. CO_2 Levels for E01 master bedroom by hour of the day and test condition.

The first question in the long-term study is whether there is adequate ventilation in the base case home without mechanical ventilation. Testing the homes with the ventilation system off was designed to answer this question. Figure 6 shows a histogram of master bedroom CO_2 levels at night with the ventilation system off and bedroom doors in both open (test condition C) and closed configurations (test condition D). The data in the figure is the average of the distributions for all the houses and has been normalized so that homes with different amounts of data are treated equally. The results for the closed door condition show higher CO_2 levels. Because no mechanical systems are moving air in this situation except for the few houses with central forced air systems, this difference is not surprising. If 1,000 ppm of CO_2 is considered a reasonable concentration, approximately a fifth of all the "no ventilation" levels are below this value. About a quarter of the levels exceed 2,000 ppm. The value of 1,000 ppm is taken from ASTM Standard D6245 as the commonly referred value for 650 ppm above an ambient outside air level of 350 ppm (now 400 ppm).

The higher CO_2 levels shown in Figure 6 are concentrated in a subset of the houses. While most houses have data above 2,000 ppm for test D, eight houses have more than half their data above this level. For test C, five houses have more than half their CO_2 data above 2,000 ppm and many have no data above this level. See the next section for more discussion of individual houses and factors that influence ventilation effectiveness.

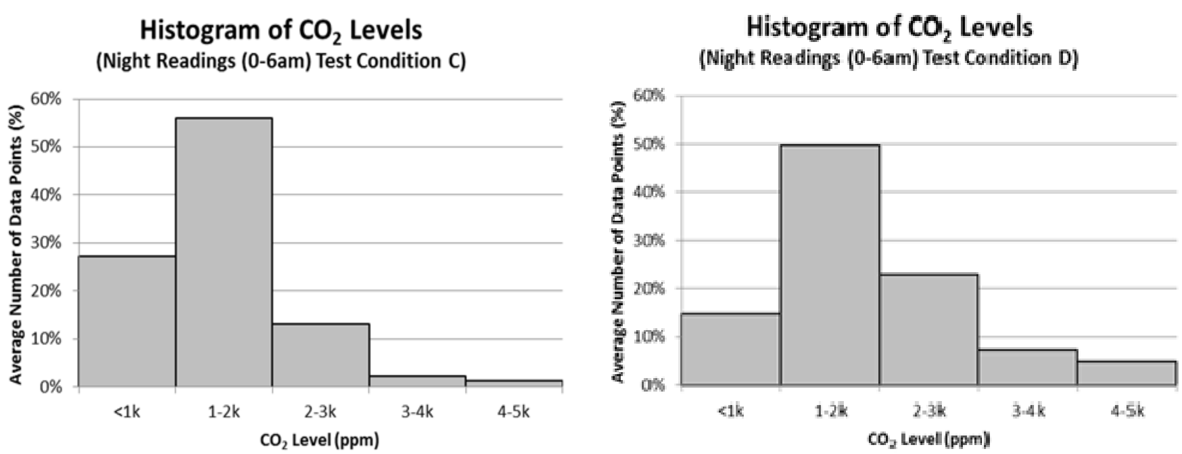

Figure 6. CO_2 levels in the master bedroom at night with doors open (C) or closed (D) and no ventilation.

Figure 7 shows the distribution of CO_2 levels for each house for each test condition. It identifies which test sites have adequate ventilation for the different test conditions. The stacked bars for each house reflect the percent of measured CO_2 levels that fall into certain bins. Green reflects CO_2 levels below 1,000 ppm. Houses that show up as mostly green for a certain test condition seem to have adequate ventilation. Red shades indicate higher levels of pollution and suggest that ventilation is not adequate. Several general observations can be made from the results shown in Figure 7:

- Missing bars in the figure indicate where a house had no data that complied with the test condition displayed.
- CO_2 levels are lowest for test A (ventilation on, doors open) and highest for test D (ventilation off, doors closed).
- Many of the houses seem to have adequate ventilation for test condition A (green), but a set of houses have CO_2 levels between 1,000 and 2,000 ppm most of the time (blue).
- When the doors are closed in test condition B, fewer houses have adequate ventilation.

- The houses that have the highest CO_2 levels when the ventilation system is off (tests C and D) also tend to have the highest levels when the ventilation system is on.
- A few houses have relatively low CO_2 levels across all the tests.

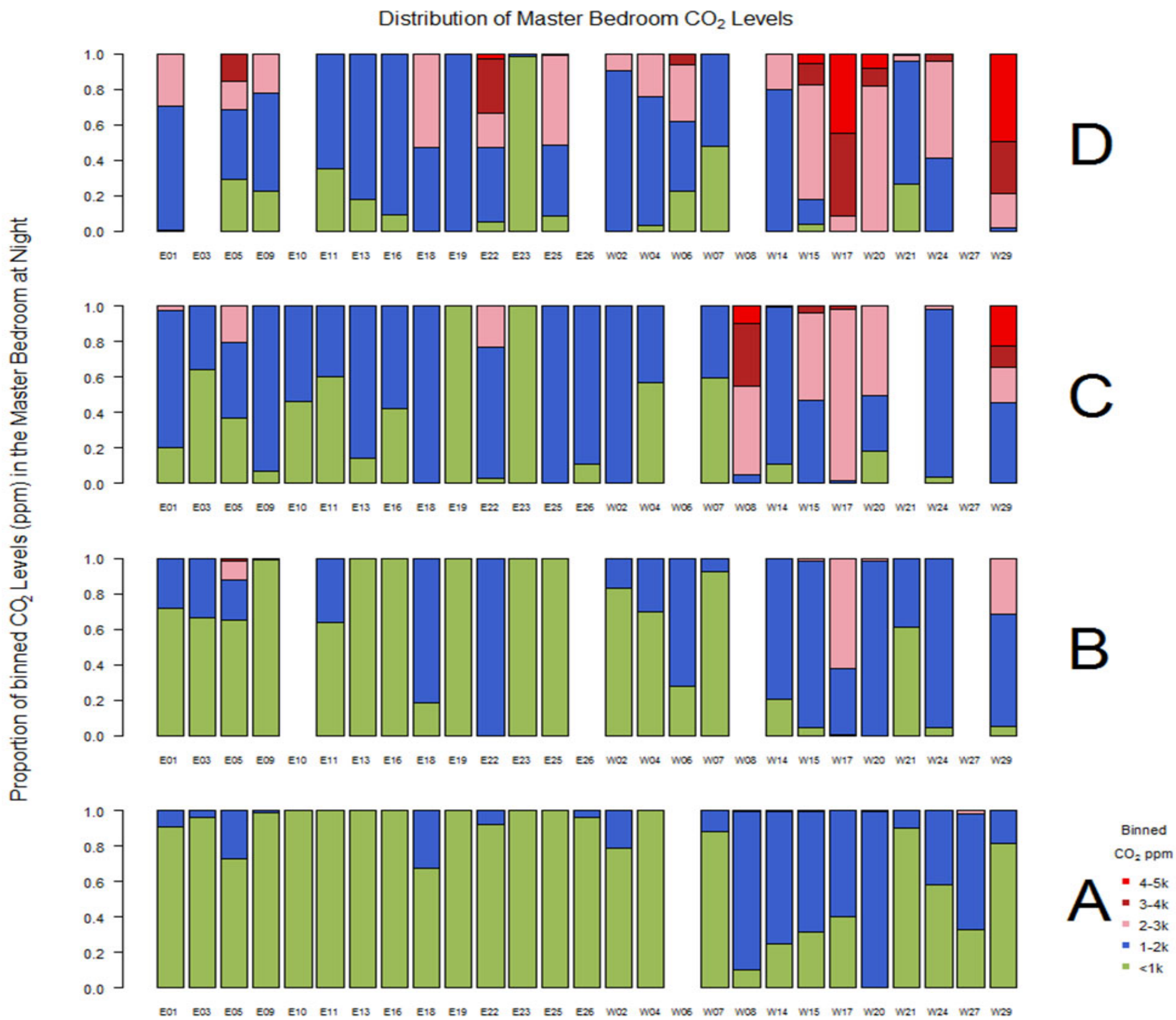

Figure 7. CO_2 level distribution in individual houses by test condition.

Additional analysis included the impacts of house air tightness, conditioned area and occupancy levels, and return pathways between rooms isolated behind closed doors and the main body of the house. The characteristics of houses with high or low CO_2 levels suggest these factors influence ventilation effectiveness. The complete analysis can be found in the project report (Eklund et al. 2013).

Home Occupant Knowledge of and Satisfaction with Different Types of Ventilation System

The WSU Energy Program team attempted to determine each homeowner's:

- Knowledge of their ventilation system and its operation and maintenance needs,

- Satisfaction with their system, and
- Interest in indoor air quality.

Levels of knowledge were assessed according to Figure 8.

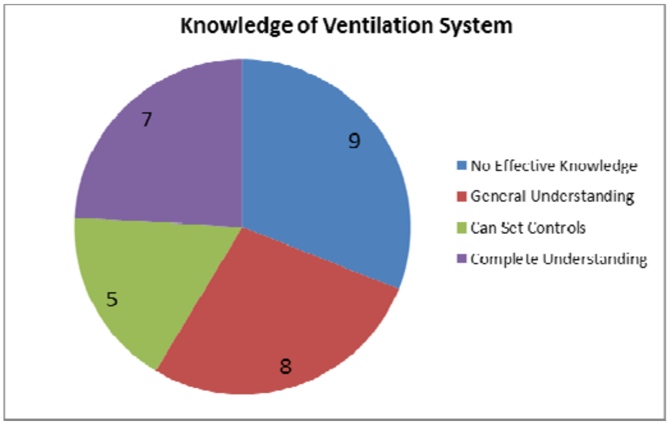

Figure 8. Spread of the four knowledge groups.

The fact that over 90% of the occupants were satisfied with their system performance and indoor air quality even though over half of them did not have enough knowledge to operate or maintain the system is troubling, especially where the lack of knowledge correlates with unresolved operation and maintenance issues found by the WSU Energy Program field staff. It means that occupant satisfaction is not a good indicator of ventilation system performance. Further, if something was seriously wrong with the system, the home occupant would probably be unable to recognize it or take appropriate action.

Problems found on initial audit included controls not set to deliver sufficient ventilation to meet standards; inaccessible controls; filters and fan housings jammed with dust and lint; disconnected ducts; HRV operation wired backwards; and ductwork never completed. Complexity of controls was also often problematic.

Conclusions

The analysis provides an initial response to the research questions by summarizing the results of the short-term analysis, considering the energy use of the ventilation systems, conducting an analysis of the long-term data for the master bedroom for six night hours (midnight to 6 a.m.) and summarizing the field work to ascertain occupants' knowledge of their ventilation systems. The key results are initial findings that can be used to identify areas for further work:

- There is a fairly wide variation of ventilation fan electricity use both within and across ventilation system types.
  - The exhaust systems have the lowest direct energy use followed by the HRV/E systems.
  - The ventilation systems integrated with central forced air systems have the highest use though there is wide variation within this small group.
- Measurements show the natural ventilation is inadequate when the ventilation systems are off and that the ventilation systems provide a clear benefit when they are turned on.

The data indicate that HRV/ERV systems offer relatively better ventilation in the master bedroom at night especially when doors are closed than exhaust systems—the other main group in the study. This is shown most clearly in the short-term test for the master bedroom with the door closed, and is supported by less clear comparative findings in the long-term data under the same test conditions. Households with the highest CO_2 levels for the "ventilation system off" tests also tended to have the highest levels when the ventilation systems were on. This suggests that other factors in the home besides ventilation system type have a significant influence on ventilation system performance. These factors include house air tightness, occupancy density and behavior, conditioned floor area, air circulation between master bedroom and main living area, and heating system type.

- The influence of other exhaust devices and household behavior has not been incorporated into the preliminary analysis. This may explain the measured data for some of the houses.
- The field work provides evidence that lack of occupant knowledge about the proper operation and maintenance of the ventilation systems can negatively influence ventilation system effectiveness. Over time, this could result in significant deterioration in system performance.
- The use of air inlet vents provides benefit only if they are open (most were found closed) and only if doors are closed during sleeping.

A more complete analysis of overall efficacy of these systems could include impacts on space conditioning and system cost. The full report includes additional finding on the condition of systems as found with regard to deficiencies in operation and maintenance (Eklund et al. 2013).

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