

Characterizing Indoor Air Quality in a Colorado Passive House: A Pilot Case Study

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SUMMARY

Passive houses are a design concept to reduce energy use in buildings by making the structure tight and insulated. Previous studies investigating indoor air quality (IAQ) in passive houses are few and far between, and show mixed results. This pilot case study characterized the IAQ of a passive house near Masonville, CO by continuously sampling the air for particulate matter (PM), carbon dioxide (CO₂), and total volatile organic compounds (TVOC). Measurements were recorded for a period of six hours while the home was unoccupied and then during prescribed activities, which included walking around to resuspend dust and particulate matter and frying an egg. Additionally, temperature, relative humidity and carbon dioxide levels in the bedroom were recorded for a period of one week during normal occupancy. Results indicate that outdoor PM had little effect on indoor levels, while walking and cooking greatly increased indoor PM. TVOC levels appeared to be independent of any inside activities. CO₂ levels were significantly increased by both activities, with cooking having a larger impact. Due to very low air exchange rates, CO₂ and PM levels were slow to decay once elevated. In the bedroom, CO₂ levels increased at night to above 1000 ppm. Overheating was not an issue in late fall, with an average temperature of 21.7°C and a maximum of 26.0°C. Relative humidity ranged from 12.2% to 34.2% with a mean of 25.3%. Overall results show generally good air quality that degrades during cooking. Thus it is recommended to supplement ventilation with open windows or doors while cooking.

KEYWORDS

Passivhaus, thermal comfort, cooking emissions, particulate matter, ventilation

1 INTRODUCTION

Passive houses are a simple idea: construct a building that is well-insulated with a tight envelope, and the result is a very energy-efficient home. A proclaimed benefit of these homes, in addition to the energy efficiency, is improved indoor air quality due to continuous mechanical ventilation and filtered incoming air. Filtering incoming air only solves one issue, however. Many of the pollutants in the home are from indoor sources. The goal of this case study was to observe and quantify how a passive house was impacted by common indoor-sourced pollutants. Previous studies have looked at the comfort and air quality of passive and tightly constructed houses (Wagner and Rosenfeld, 1982; Langer, et al. 2015, Foster, et al. 2016), but these studies are few and far between, and indicate a need for further research. Human activity in the home has also been shown to dramatically increase airborne pollutants (Thatcher and Layton, 1995; Qian et al. 2014), and so experiments were done to study how these activities affect tightly-constructed houses. With the growing number of energy-efficient homes in the U.S., it is important to characterize these types of homes by their impacts to indoor air quality. In this study, we characterized the air quality under a series of activities, and compared the results to known air quality standards.

2 MATERIALS/METHODS

House Selection

The target for this case study was a house that was constructed or retrofitted to Passive House Standards. These standards are set by one of several organizations, including the Passivhaus Institut (PHI) in Europe and the Passive House Institute U.S. (PHIUS). While these organizations have slightly differing standards, they both have strict guidelines on the tightness and energy use of a home. The home selected for this study was certified to PHI standards by the Passive House Academy (PHA). The tightness of the 1275 sq. ft. (119 m²) home was verified by PHA at 0.5 air changes per hour while pressurized at ± 50 Pa (ACH₅₀). The standards require an ACH₅₀ of 0.60 or less. The home features an Air Pohoda Ultima240 heat recovery ventilator (HRV) that provides approximately 50 cubic feet per minute (cfm) (23.6 L/s) of outdoor air continuously under standard operation. This flowrate equates to an overall air exchange rate of roughly 0.16 h⁻¹ based on an owner-provided volume of 18,850 ft³ (534 m³). The downstairs bedroom receives 9 cfm (4.25 L/s) of fresh air, giving an air exchange rate of approximately 0.25 h⁻¹ based on dimensions from the architectural plans. See Figure 1 for the ventilation distribution.

Data Collection

Air quality was monitored indoors and outdoors for the testing periods. The home was first monitored for six hours while unoccupied to get a baseline for undisturbed air, then also during several prescribed activities (described below). The downstairs bedroom was also monitored for a week-long period after the activities were performed. See Table 1 for the list of parameters that were monitored.

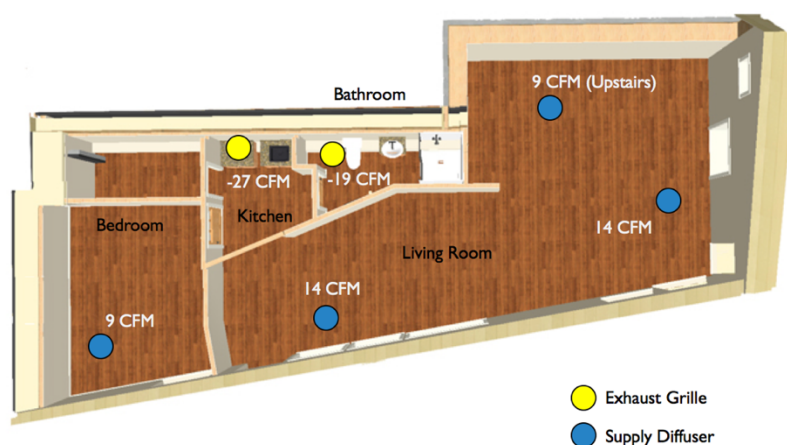


Figure 1. Ventilation distribution in house

Table 1. Air quality measuring equipment and measured pollutants

Equipment	Pollutant	Measurement Period
Outdoors		
Dylos DC1700	Particulate Matter (PM)	6 hours + Activities
TSI Q-Trak	Carbon dioxide (CO ₂)	20 min. for baseline
Indoors (Living Room)		
Dylos DC1700	PM	6 hours + Activities
GrayWolf DirectSense TVOC	Total Volatile Organic Compounds	6 hours + Activities
TSI Q-Trak	CO ₂	6 hours + Activities
	CO	6 hours + Activities
Indoors (Bedroom)		
TSI Q-Trak	CO ₂	1 week
	Dry-bulb Temperature	1 week
	Relative Humidity (RH)	1 week

Equipment was placed at a height between 0.5 and 2 meters, and at least 1 meter away from any doors or operable windows. See Figure 2 for equipment layout.

Activities

Two repeatable prescribed activities were performed in the house to test the “performance” of the indoor environment. Activities consisted of the following:

- Active Movement (Particle Resuspension) – Two people entered the living room and proceeded to walk around for ten minutes (one person for Visit #2). The goal was to measure the levels of particulate matter and observe the re-suspension and re-deposition of particulate matter due to an occupant’s movement.
- Cooking – One egg was fried in one tablespoon of canola oil on an uncovered stainless steel skillet over “medium” heat for a duration of six minutes (three minutes on each side). The oil was preheated for one minute prior to cooking the egg. The goal of this experiment was to quantify the impact of cooking in a passive home and observe the duration and for which the air quality was affected. In this home, there was no range hood to vent the cooking fumes, however, the kitchen area should be negatively pressurized with respect to the living room based on the ventilation distribution layout (Figure 1). For Visit #1, the small burner was used on medium heat. For Visit #2, the larger burner was used on low because the smaller burner wasn’t working. Even at its lowest setting, it still appeared to produce more heat than the smaller burner. The results appear to reflect this difference.

Analysis

Data from the equipment was not always output in the desired units. The particle counters (Model DC1700, Dylos, Inc.) provide fine ($>0.5\ \mu\text{m}$) and coarse ($>2.5\ \mu\text{m}$) particle counts. By subtracting the coarse from the fine, we arrived at an approximate $\text{PM}_{2.5}$ particle count, that is, the number of sampled particles smaller than $2.5\ \mu\text{m}$. A particle count is not inherently useful for comparing to known standards, which are typically reported in $\mu\text{g}/\text{m}^3$. To convert to this mass concentration, we used the calibration coefficient for fresh particles determined by Dacunto, et al. (2015).

Data from the TVOC monitor (DirectSense TVOC, GrayWolf Inc.) was reported in part per billion (ppb) based on isobutylene as a reference molecule. Many standards for VOCs report in $\mu\text{g}/\text{m}^3$ as well. To convert from ppb to these units, the mole fraction was multiplied by a correction factor of 0.5 (isobutylene to toluene), then converted to mass using toluene as a reference molecule as done by Noguchi, et al. (2016).

Data from all other equipment was reported as logged. Statistical analysis was not performed, but recorded values were compared to known standards. Air exchange rates were calculated using a completely mixed-flow reactor model with carbon dioxide as the gas.

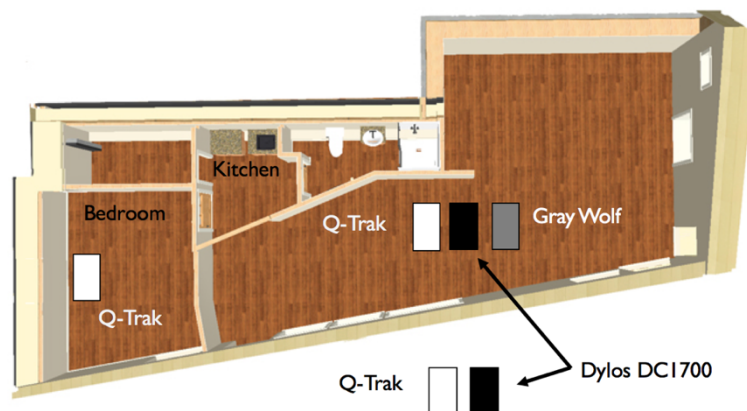


Figure 2. Air monitoring equipment layout

3 RESULTS

Living Room

Walking around to resuspend dust caused a small but noticeable increase in particulate matter. Cooking the egg had a much bigger impact on the air quality. Particulate matter and carbon dioxide increased substantially to the peak values listed in Table 2. Although there was an increase, carbon dioxide levels never reached uncomfortable levels, likely due to the large open volume of the living room and connected spaces. Particulate matter did reach considerably high levels: approximately five times the National Ambient Air Quality Standards (NAAQS) set by the Environmental Protection Agency (EPA). Although the PM_{2.5} levels drop to below these levels within a few hours, it is possible that repeated exposure to the peak levels could pose a health risk. Plots of the PM_{2.5} levels during the activities are shown in Figures 3 and 4, for the first and second visit, respectively. An air exchange rate of 0.14 ACH was calculated from the carbon dioxide decay rate, which is similar, but even lower than the estimated rate of 0.16 ACH determined from the plans.

Table 2. Summary of air quality measurements for activities

Parameter	Baseline		Peak		Standard	Notes
	Visit 1	Visit 2	Visit 1	Visit 2		
Walking						
PM2.5 (µg/m³)	1.5	1.4	10.8	4.5	35	NAAQS: for 24 hrs; 3-yr avg.
CO2 (ppm)	-	433	-	461	1000	ASHRAE Std. 62.1
TVOC (µg/m³)	-	191	-	213	500	USGBC - LEED
Cooking						
PM2.5 (µg/m³)	1.5	1.4	81.6	180.3	35	NAAQS: for 24 hrs; 3-yr avg.
CO2 (ppm)	-	433	-	557	1000	ASHRAE Std. 62.1
TVOC (µg/m³)	-	191	-	229	500	USGBC - LEED
Outdoors						
PM2.5 (µg/m³)	2.6	2.3	225.4	112.8	35	NAAQS: for 24 hrs; 3-yr avg.
CO2 (ppm)	-	350	-	-	-	

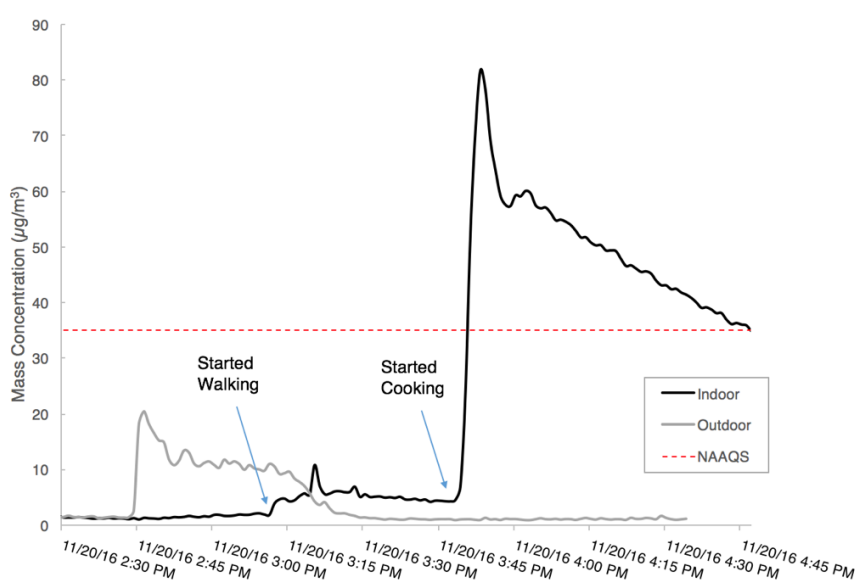


Figure 3. PM_{2.5} levels indoors and outdoors during activities for first visit

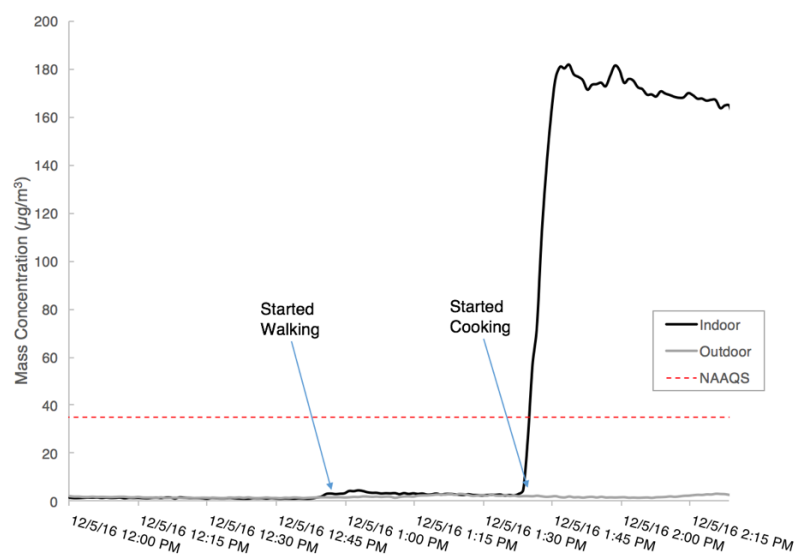


Figure 4. PM2.5 levels indoors and outdoors during activities for second visit

The particulate levels dropped more rapidly during the first visit than the second visit likely due to the door being opened to enter and exit approximately four times. The door was kept shut for a period of one hour after cooking for the second visit.

TVOCs during the experiment appeared to be independent of the walking and cooking. The gradual increase in levels throughout the day, even before the activities began, was likely due to outdoor sources or increased off-gassing of materials from increasing temperatures. These results for the VOCs can be seen in Figure 5.

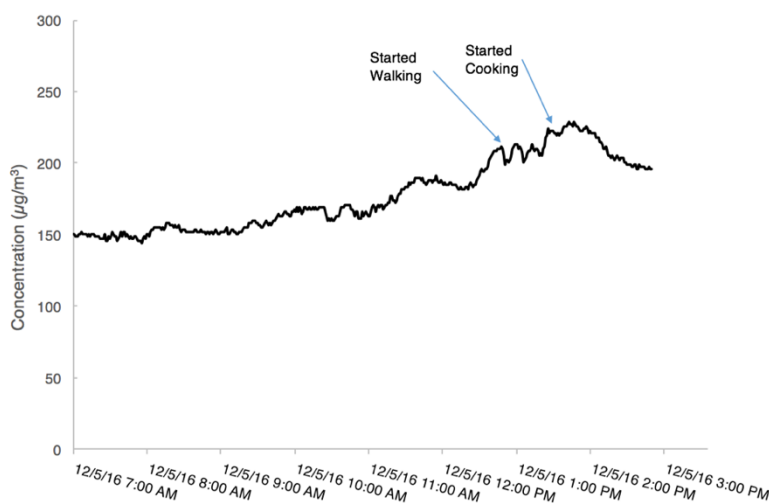


Figure 5. TVOC concentrations from baseline to activities

Bedroom

Over the course of a week, the bedroom had one or two people occupying it. Results from this week can be seen in Table 3. The peak values occurred at night with two people sleeping and peak temperatures occurred during the day. Carbon dioxide levels, although exceeding ASHRAE recommendations for comfort, do not pose a health threat. The decay rate of the carbon dioxide was used to calculate an air exchange rate of 0.15 ACH, lower than the estimated 0.25 ACH determined from the plans.

Table 3. Measurement results from bedroom over one week

Parameter	Minimum	Maximum	Mean
Temperature (°C)	18.6	26.0	21.7
Relative Humidity (%)	12.2	34.4	25.3
Carbon dioxide (ppm)	408	1396	734

4 DISCUSSION

Regular activities, like sleeping and walking, did not produce high levels of pollutants. Even though the CO₂ at night may be less than ideal, they did not exceed ASHRAE comfort recommendations by much. Cooking, on the other hand, was a strong source of particulate matter that could be harmful to one's health. In homes with higher air exchange rates, the levels would drop reasonably quick, mitigating the health risks. However, in this home, the low ventilation rate kept the particulate levels high for an extended period of time.

5 CONCLUSIONS

The passive house studied here had generally good air quality overall that degraded significantly during cooking. Most homes do have temporary increases like this, but the issue is exacerbated by the low ventilation rate in this passive house. Opening a window during cooking would likely reduce the particulate levels more rapidly. Even so, it is recommended that the heat recovery unit providing the ventilation be turned up to a higher rate when the home is occupied. Further research is encouraged to determine if other passive houses experience similar issues.

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