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Assessing Occupant and Outdoor Air Impacts on Indoor Air Quality in New California Homes

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ABSTRACT

In 2008 the State of California adopted new building codes that required the use of mechanical ventilation systems in homes that meet the requirements of ASHRAE Standard 62.2. The standard requires both a dwelling unit mechanical ventilation system and exhaust fansin kitchens and bathrooms. A field study was undertaken to evaluate the IAQ and ventilation performance of homes built to these requirements. For ventilation system performance, the airflows of all mechanical ventilation systems were measured and their use was monitored for a one-week period. To evaluate IAQ, key pollutants were measured indoors and outdoors during the week, and occupants completed satisfaction surveys. The key pollutants included: formaldehyde, humidity, PM2.5 and NO_2. Passive samplers were used to determine average concentrations for the week. Active samplers were used to develop time-series results that can be used to correlate pollutant concentrations with occupant activities. Other ventilation/IAQ related parameters were also recorded, such as stove top temperatures to indicate cooking, exterior door contact switches to know when large openings were being used for ventilation and sensors to determine when clothes dryers were being used. The building envelope and duct leakage were measured to enable estimatesof infiltration and duct leakage effects. This paper presents an overview of the test procedures and preliminary results from several homes. The results show that although average concentrations may be reasonable compared to available standards (with the exception of formaldehyde), occupants have a strong impact on pollutant variability and source strength and that outdoor concentrations cannot be ignored. Overall, these mechanically ventilated homes have reasonable IAQ. The homes and duct systems are moderately tight, though not excessively so, by US standards. Significant concerns have been expressed regarding compliance with the ventilation requirements in the California building code. However, almost all the ventilation systems in this study complied with the ventilation air flow requirements and on average were significantly higher than the minimum required air flow rates.

KEYWORDS

ASHRAE 62.2, Pollutant measurement, Formaldehyde, Mechanical Ventilation, Compliance

1 INTRODUCTION

This paper presents methods and preliminary results from the Healthy Efficient New Gas Homes (HENGH) field study for the California Energy Commission. The field study is collecting data on ventilation systems and indoor air quality (IAQ) in California homes built since the2008 update of the state's residential energy efficiency standards first required dwelling unit mechanical ventilation (CEC, 2008). Data are being collected on ventilation system designs and specifications, installed equipment performance and use, air contaminant concentrationsand environmental parameters, and resident perceptions of indoor environmental quality. The focus of the study is on evaluation of IAQ when windows are closed and mechanical ventilation is operating. Measurements includeone-time diagnostic testing of building and equipment performance and week-long monitoring of equipment use, pollutant concentrations, and pollutant-related activities. All the homes in the study are "new"and located in California. "New" homes for this study means homes that were built to meet Title 24 and be mechanically ventilated to meet ASHRAE Standard 62.2.The study target is to collect data in about 70 homes in total. In this paper, we report results from the first 16 homes. The pollutant data are all from time-integrated measurements. Data from additional homes and analyses exploring time-resolved data to investigate associations of ventilation, pollutant concentrations and occupant activities will be presented in subsequent papers.

2 FIELD MEASUREMENT PROCEDURES

More details regarding the field testing protocols can be found in Chan et al. (2016). The field test protocol was approved by the LBNL Human Subjects Committee.

The following general characteristics are determined for each home:

- Floor area, year of construction, number of stories, and number of occupants.
- Floor plan showing number and location of all bedrooms and bathrooms.
- Locations and rated airflows of all ventilation equipment (marked on floor plan).
- Number and location of all gas burning appliances, such as furnaces, water heaters, ovens, cooktops, and gas fireplaces.

2.1 Home Diagnostic Measurements

The following diagnostic tests are performed at the beginning of the testing on each home in order to obtain information relevant for ventilation and IAQ assessments:

- Envelope air tightness is determined using multi-point blower door tests following the procedures and calculations in ASTM E779 (ASTM 2010). Envelope air tightness is expressed at Air Changes per Hour at 50 Pa (ACH50).
- Duct air tightness is determined using the “DeltaQ” approach that measures the duct leakage to outside for supply and return ducts under normal operating conditions following the procedures and calculations in ASTM E1554 (ASTM 3013).
- All mechanical system air flows: home ventilation system, kitchen and bathroom exhausts.

2.2 Indoor activity monitoring

Many indoor pollutants are associated with occupant activities: moisture and VOCs from cooking, cleaning and bathing, CO_2 from metabolic activity, and CO_2, NO_2, moisture and particles from cooking. The following are continuously monitored during the test week and recorded using various devices:

- Cooktop and oven use using thermal sensors placed directly on the cooking surfaces
- Fireplace use using temperature sensors (no fireplace use was recorded in any of the current homes during our monitoring).
- Bathroom, kitchen and other exhaust fans using motor sensors or small data-logging anemometers to record when these fans operate and at which setting.
- Clothes dryer use using a motor on/off sensor and logger.
- Central forced air system operation from measuring air temperature at a supply register of the central forced air system.
- Opening/closing of doorsusing micro-switches. Only select doors and windows were monitored based on input from the occupants on those that were used most often. This information is critical because there are large ventilation air flows associated with these openings and estimating the impact of mechanical ventilation systems is very difficult if conflated with window or door opening.

2.3 IAQ Measurements

Temperature and relative humidity are measured outside the home and at multiple locations in the home, primarily in the main living area, bedrooms and bathrooms. Pollutants are measured using the instruments (and locations) listed in Table 1. The outdoor measurements are critical for pollutants whose outdoor levels can be significant – particularly PM2.5 for which a major source can be outdoor air. The pollutants were chosen based on their potential health impact and ubiquity and include the major pollutants of concern determined from previous studies (Logue et al. (2012)). The multiple locations for some sensors provide some indication of the spatial variations of formaldehyde exposures inside the study homes. Temporal variations are evaluated using sensors with high time resolution. Because the real-time NO2 and formaldehyde real-time sensors can have significant calibration issues passive samplers are also used, e.g., the performance of the real-time formaldehyde monitors (Carter et al., 2014) had been tested in laboratory setting but not in field applications. The results from the passive samplersare used as a calibration check for the real-time measurements.

Table 1 IAQ measurements during one-week sampling period

Parameter	**Instrument**	**Indoor Location(s)**	**Outdoor**
PM2.5	MetOne ES-642/ BT-645	Central location	Yes
CO_2	Extech SD-800	Central location, master and other bedrooms	--
NO_2	Aeroqual NO_2 monitor	Central location	--
	Passive Ogawa samplers	Central location	Yes
Formaldehyde	Shinyei formaldehyde monitor	Central location, master bedroom	--
Formaldehyde/ acetaldehyde	SKC UMEx 100 passive sampler	Central location, master bedroom	Yes

PM2.5 is monitored both indoors (MetOne BT-645) and outdoors (MetOne ES-642) in real-time. The light source and sensor of these two nephelometers are identical so that the measured concentrations can be compared. The ES-642 has a heated inlet to handle high humidity that may be encountered outdoors. PM2.5 concentrations are recorded at a one-minute time interval.

$CO_2$is monitored at multiple indoor locations as an indicator of bioeffluents. The Extech SD-800 is used to measure CO_2 concentrations, as well as temperature and relative humidity, at a one-minute time interval.

NO_2 is a combustion related air contaminant of interest. Real-time NO_2 concentrations are used to characterize contributions from cooking and other indoor sources. The Aeroqual monitor is used to measure NO_2 concentrations at a one-minute time interval. It is suitable for indoor use only. In addition, $NO_2$is measured using passive samplers both indoors and outdoorsto obtain a time-integrated NO2 value that can be used to calibrate the Aeroqual measurements (from indoor results) and as a measure of outdoor concentrations.

Formaldehyde concentrations are measured at 30-minute time interval at the central indoor location and also in the master bedroom. Passive samples are collected using SKC UEMx 100 samplers in the same locations as the real-time monitors. The passive samplersare also be used to measure formaldehyde concentrations outdoors.

3 SUMMARY AND RESULTS OF FIELD IAQ MEASUREMENTS AND HOME CHARACTERISTICS

The results of this study are compared to those of a prior study of ventilation and indoor air quality in new homes in California (Offermann, 2009). In that study, pollutant concentrations and air exchange rates were measured over a single day and window use was monitored over a week in 105 California homes that were built in 2002-2004 and measured in 2005-2007. The homes in the prior study were built and tested before the State of California required mechanical ventilation or limited the formaldehyde allowed in building products. We also compare the results to relevant guideline exposure limits.

Table 2 summarizes the home characteristics. Compared to state and US national averages these homes are fairly representative of new construction. The floor area is typical of new California homes but larger than the US average of about 200 m^2 (US Census Bureau). Analysis of blower door tests in California homes for the RESAVE project (Sherman et al. 2013) showed that homes built since 2000 have an average air leakage of 4-5 ACH50. Data from another recent California study (Proctor et al. 2011) showed a median of 4.7 ACH_{50} for single-family homes. For comparison, the IECC (2013) that is used in many US states and energy programs would require most of these homes to be less than 3 ACH50. Only two of the sixteen homes tested so far in the HENGH study were below 3 ACH50.

Table 2 IAQ Home Characteristics and Diagnostic Test Results

	Mean	**Range (Min- Max)**
Size (m^2)	252	156 – 390
# of Bedrooms	3.6	3 - 5
# of Full Bathrooms	2.9	2 - 5
Built Year	2014	2011- 2015
Number of Occupants	2.6	1 - 8
Envelope Tightness (ACH50)	5.0	1.8 - 7.8
Duct Leakage (%)	8	1.5 – 38
Min. required dwelling unit mech. ventilation (L/s)	29	22 - 41
Dwelling unit mech. ventilation (% of min. required)	152	71- 218

Duct leakage is important in ventilation and IAQ studies because duct leaks act like mechanical ventilation and even a fairly small duct leak can have a much bigger effect on ventilation than the designed home ventilation system. For example, at a typical forced air system flow for these homes of 600 L/s, 6% leakage is an air flow of 36 L/s from outside; this is similar to the mechanical ventilation system flow, as noted in Table 2. In addition, if the duct leakage is from locations that may have higher pollutant levels than indoors (e.g., from chemical storage in a garage) then this duct leakage may draw pollutants into the home. In our study 13 homes had valid duct leakage test and nine homes meet the duct air tightness requirements for California homes, i.e., 6% of total system air flow. The average duct leakage is much higher than the median due to one outlier at 38%.

The dwelling unit mechanical ventilation systems are predominantly exhaust (13 out of 16 homes) extracting from a wet room, typically the laundry room. The other three homes had supply systems integrated into the central forced air duct system. California State Energy Code (Title 24) refers to ASHRAE 62.2-2008fan sizing equation for its ventilation requirements. The California code does not allow for any infiltration credit (other than the 0.1 L/m^2 default infiltration credit assumed in the fan sizing equation). The individual home minimum flow requirements and installed flows are given in Table 3. On average the mechanical systems are oversized compared to the fan size required by Title 24by about 50%.This oversizing indicates that there is the potential for some energy savings.Two systems did not have sufficient air flow to meet the minimum requirements, one of which was more than 20% undersized. Similar oversizing was reported by Stratton et al.(2013) from measurements in 15 California homes in 2010: dwelling unit ventilation systems averaged 40% larger than the minimum requirements and 2 of the 15 systems had too little flow.

Table 3.IAQ Home Characteristics and Diagnostic Test Results

House	Min. required flow (L/s)	Dwelling unit mechanical ventilation (L/s)
3	32.0	47.0*
5	39.0	51.7
6	28.7	54.1
7	32.9	44.7
10	40.9	89.3*
15	24.0	33.4
16	31.5	27.7
8	28.7	47.9
9	32.0	47.0*
11	25.9	38.1
4	28.2	20.2
13	23.0	40.9
17	24.0	41.4
21	31.5	48.4
19	25.9	52.2
24	22.1	33.4
Mean	**29.4**	**44.8**
STDEV	**5.4**	**15.1**

*Supply system, rated fan airflow (not masured)

Table 4 Range Hood Exhaust Flows

	Mean	Median	Range (Min- Max)
High setting (L/s)	167	101	48–493
Low setting (L/s)	69	54	27– 170

Table 4summarizes the range hood air flows. For kitchen ventilation, all of the homes met the minimum requirement of 50 L/s on the high setting and nine on the low setting. All of the homes used range hoods vented to outside. Half of the range hoods had an integrated microwave oven. For bathroom ventilation, all the exhaust fans met the 25L/s minimum air flow requirement. For comparison, about 1/3 of the Stratton et al. (2013) homes had bathroom fans (48 total) that did not meet the minimum 25 L/s requirement of ASHRAE 62.2, but all four of the measurable kitchen range hoods did meet the minimum 50 L/s requirement. In general, these homes are meeting the requirements for installed exhaust fans in kitchens and bathrooms. A key issue with both kitchen and bathroom ventilation is how they are operated. For kitchen exhaust it is at the discretion of the occupants. For bathrooms there were humidity controls (whose setpoint is fixed by the installer) in 11 of the 16 master bathrooms and 29 of the 46 total bathroom fans. In future work we plan to compare estimates of cooking operation (using stove top temperatures) to range hood operation and measured bathroom temperatures and humidities to bath fan operation to see how often these fans are used as needed by occupants.

A key observation regarding the dwelling unit ventilation systems is that all but one of them were turned off when the field investigation teams first attended the homes. For the purposes of our study we turned these systems on. Note that in ASHRAE 62.2 and California Title 24 it is a requirement to have a clearly labelled switch for this system that can be used by occupants to turn it off (or on) and there is little or no occupant education as to what this switch is doing to the home. However, ten of the homeowners claimed to know how to use the ventilation system (but had turned it off anyway).

Table 5 summarizes the results of the week-long, time-integrated measurementsofformaldehyde and NO_2.The formaldehyde concentrations were similar in the master bedroom and common room of each home, but varied by more than a factor of three across homes. As a group, formaldehyde concentrations in the HENGH study are lower than those reported by Offermann(2009) for homes built 2002-2004, which had a median of 36 µg/m^3, and range of 5–136µg/m^3) and the 32 µg/$m^3$from other studies quoted by Offermann.The meanformaldehyde concentrations fall somewhere between the 9 µg/m^3 chronic Reference Exposure Limit (REL) and 55 µg/m^3 acute REL from California's Office of Environmental Health Hazard Assessment. One home in our study was at the acute formaldehyde REL in the bedroom.Time-integrated NO_2 concentrations in all homes were well below the California annual (i.e. long-term) air quality standard of 57 ug/m^3. The average of 7.9 µg/m^3across the first 16 HENGH homes is a little higher than the mean of 5.7 µg/m^3 reported by Offermann for the 29 homes in which it was measured in that study. NO2 concentrations were much lower than the levels reported by Mullen et al. (2016) for California homes with gas appliances.

Table 5 Time Integrated results for Formaldehyde (HCHO) and NO_2

House	HCHO Livingroom (µg/m^3)	HCHO Bedroom (µg/m^3)	HCHO Outdoor (µg/m^3)	NO_2Livingroom (µg/m^3)	NO_2Outdoor (µg/m^3)
3	NA	NA	NA	3.8	1.9
5	NA	NA	NA	6.6	7.2
6	48	55	3.1	6.0	2.8
7	30	34	3.1	15.5	5.7
10	28	26	3.1	26.1	6.2
15	29	30	3.6	NA	NA
16	52	55	2.9	5.5	15.5
8	34	33	2.3	2.1	6.8
9	29	21	2.6	7.2	2.3
11	32	30	2.7	6.4	3.8
4	26	21	1.8	4.5	3.6
13	18	19	1.6	4.3	7.4
17	19	18	1	2.3	4.7
21	22	23	2	5.1	5.9
19	17	24	2.3	13.2	1.9
24	15	15	3	9.6	4.2
Mean	**28**	**29**	**2.5**	**7.9**	**5.3**
STDEV	**11**	**13**	**0.7**	**6.3**	**3.4**

The results in Table 6 show that on average the PM2.5 levels are lower indoors than outdoors and only four homes had higher average indoor concentrations than outdoors. This implies that outdoor air is a significant source of indoor PM2.5. PM2.5 indoors and outdoors is characterized by high periodic events (and minimums that are essentially zero) as shown by the extreme maximum values in some homes and outdoor conditions that are two orders of magnitude above the mean. Compared to WHO guidelines, the average PM2.5 concentrations are below the annual level of 10 µg/m^3. These are lower than the 24 hour time-integrated results averaged over 31 homes in Offermann, of 13 µg/m^3indoors and 8 µg/m^3 outdoors. The maximum levels exceed the 24 hour guideline level of 25 µg/m^3 but these maximum levels were for time periods much less than 24 hours.

Table 6Summary of time-resolved indoor and outdoor PM2.5(µg/m^3)

House	Living room				Outdoor		
	Mean	**Minimum**	**Maximum**	**Minutes> 25 µg/m^3**	**Mean**	**Minimum**	**Maximum**
3	5.9	1	27	15	2.4	0.6	13.2
5	1.1	0	8	X	3.3	0.7	15
6	NA	NA	NA	NA	4.8	0.7	48.2
7	2.3	0	9	X	4.5	0.7	514
10	4.2	0	112	113, 28, 32	2.5	0.02	82.5
15	2.3	0	32	5	3.8	0.01	53
16	1.7	0	50	1	8.3	1.6	63
8	1.5	0	26	1	2.2	0.01	65.1
9	2.6	0	14	X	3.6	0.7	25.9
11	0.1	0	3	X	1.7	0.7	10.9
4	11	0	493	367, 228 (oven cleaning)	5.1	0.01	63.5
13	0.9	0	12	X	15.7	0.7	82.4
17	4.5	0	98	42, 456, 3	15.5	0.7	315.8
21	10.6	5	65	92	8.2	0.7	77.9
19	3.0	0	298	40, 130	3.4	0.02	45.3
24	2.8	0	191	182	0.1	0.04	0.9
Mean	**3.6**				**5.3**		

Table 7 Summary of time-resolved CO_2 for the Living Room and Master Bedroom

	Living Room CO_2 (ppm)		Master Bedroom CO_2 (ppm)	
House	**Average**	**Highest 1 hr**	**Average**	**Highest 1 hr**
3	834	1176	849	1264
5	681	989	740	1024
6	608	820	686	1015
7	626	873	644	1030
10	638	974	760	1216
15	730	1345	751	1101
16	761	1008	706	918
8	555	650	610	821
9	569	690	643	965
11	578	859	568	694
4	520	818	607	785
13	618	1003	662	995
17	512	668	510	627
21	575	845	720	1163
19	564	963	665	1098
24	576	952	762	1280
Mean	**622**	**915**	**680**	**1000**
STDEV	**89**	**181**	**85**	**193**

Table 7 shows that the average and highest one-hour CO_2 in the common living space was lower than that in the master bedroom in almost all homes. This is consistent with other studies that have found higher CO_2 concentrations in bedrooms, owing to the extended period of occupancy in a room that commonly has a door closed overnight.The average of 622 ppm indoors is very close to the 610 ppm found by Offermann.

The mean indoor temperature in the test homes averaged 22.5˚C, and varied from a low of 18˚C to a high of 27˚C. During the test week, indoor temperatures were relative constant; the mean of the standard deviationsacross homes was 0.8˚C. There was more variability in relative humidity (RH). The mean over all homes was 46% with a standard deviation between homes of 8% RH. On average the range from minimum to maximum RH for each house was 15% RH. No home recorded a value above 70% RH, only one home had a maximum above 65% and three homes were above 60%.

The home ventilation rates were estimated by combining the known mechanical ventilation system air flows (including kitchen, bathroom and dryer exhaust operation) and their operating time with natural infiltration calculated from the measured air tightness using the enhanced infiltration model from the ASHRAE Handbook of Fundamentals, Chapter 16 (ASHRAE 2013).Table 8 summarizes the time-average air change rates combining infiltration and mechanical ventilation over the week of testing. We also calculated the effective ventilation rate that is required if average pollutant concentrations are to be calculated. For the HENGH homes, the standard deviation of the sample of individual home ventilation rates was about 30% of the mean. The mean difference between time-averaged and effective ventilation rates is only 0.02 ACH. The average of 0.37 ACH is close to historical US targets of 0.35 ACH for ventilation but lower than many European requirements. One home (19) had extremely high ventilation due to both master bathroom exhaust fan, and laundry room exhaust fan continuously running during the test period. One home (4) has a very low calculated ventilation rate due to inadequate dwelling unit mechanical ventilation fan flow.

Table 8Mean and Effective Ventilation Rates

House	**Time-averaged ventilation rate (Mechanical + Infiltration) (ACH)**	**STDEV**	**Effective Ventilation Rate (ACH)**
3	0.20*	0.04	-
5	0.33*	0.09	-
6	0.08*	0.21	-
7	0.18	0.07	0.15
10	0.52	0.11	0.50
15	0.27	0.03	0.27
16	0.29	0.03	0.29
8	0.25	0.08	0.23
9	0.27	0.05	0.26
11	0.24	0.07	0.23
4	0.09	0.06	0.08
13	0.45	0.19	0.38
17	0.35	0.13	0.31
21	0.37	0.14	0.32
19	1.17	0.16	1.10
24	0.79	0.09	0.78
Mean	**0.37**	**0.10**	**0.36**
STDEV	**0.27**		

- leakage test data were not available – mechanical air flows only

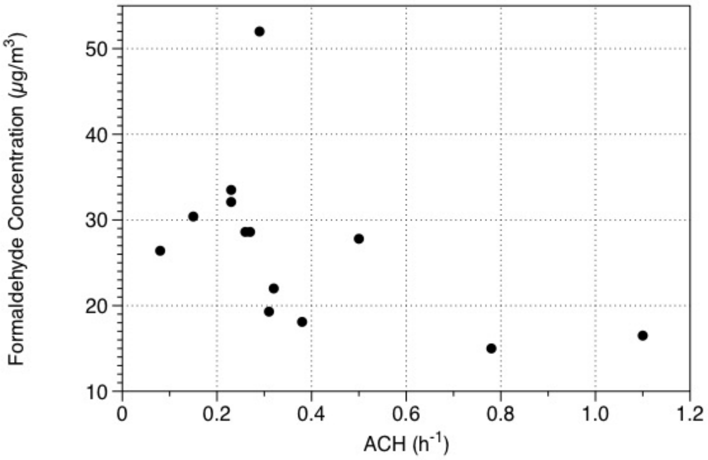

Figure 1. Dependence of Formaldehyde Concentration on Effective House Air Change Rate

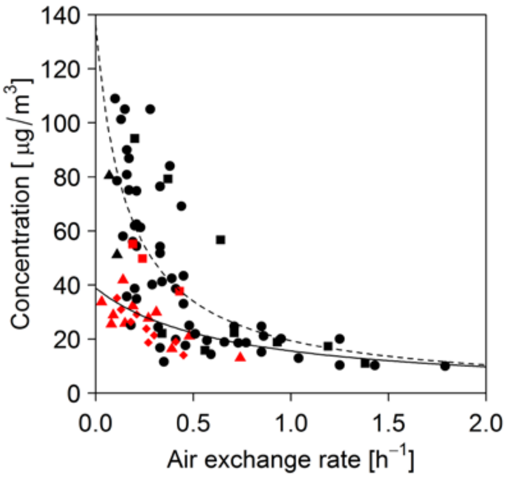

Figure 2. Dependence of Formaldehyde Concentration on House Air Change Rate from Hult at al. (2015).

Figure 1 shows how the average Formaldehyde concentration varies with the effective air change rate. A similar dependence of Formaldehyde concentration on air change rate was observed by Hult et al. (2015), as shown in Figure 2.

4 CONCLUSIONS

Although these results are from a subset of study homes some preliminary conclusions can be drawn. Overall these homes showed good compliance with installed mechanical ventilation requirements.However, due to being turned off almost none of the dwelling unit ventilation systems were operating. It was not always clear who turned them off; but there is evidence that it was the occupants in at least some of the cases. The pollutant concentrations were similar to previous studies in California and the only levels of concern are for Formaldehyde. The results show that increasing ventilation rates would be a good method for reducing formaldehyde concentrations.

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