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Ventilation and Measured IAQ in new US homes

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ABSTRACT

As newer homes are being built tighter than the existing housing stock, questions have been raised about the concentrations of pollutants of concern in new homes and how mechanical ventilation systems can address this issue. This study measured pollutants of concern in 70 new homes with mechanical ventilation in California, USA and compared the results to a previous study of home without mechanical ventilation. The key pollutants were measured using both time-integrated and time-resolved over a one-week period and included formaldehyde, PM2.5 and NO_2. Each home was tested for air flows of mechanical systems, together with house envelope and forced air heating and cooling duct leakage. The results show that the homes complied with dwelling unit ventilation fan flows and most of the time with kitchen and bathroom requirements. The measured pollutant concentrations were almost all within acceptable limits and showed that the installed ventilation flow rates (that complied with California building standard and ASHRAE 62.2 requirements) provided acceptable indoor air quality. The mechanically ventilated homes had more consistent ventilation, resulting in less extreme pollutant concentrations. However, there remain issues with system operation, e.g., poor labeling of easily accessible controls led to three-quarters of the dwelling unit ventilation systems being turned off when homes were first visited for this study. This paper summarizes the results of the diagnostic testing and time-integrated field measurements, together with implications for ventilation standards.

KEYWORDS

Ventilation performance; formaldehyde; nitrogen dioxide; particles; field study

1 INTRODUCTION

This study aimed to answer the question: Do current U.S. ventilation requirements in new homes result in acceptable indoor air quality? To answer this question we performed diagnostic tests and field measurements of pollutants in 70 new California homes that have mechanical ventilation. This was part of the Healthy New Gas Homes (HENGH) study – a joint US Department of Energy and California Energy Commission study that also included occupant surveys in over 2700 homes and energy simulations to determine optimum air tightness. The complete study can be found in Chan et al. (2018) and is available as a contributed report to the AIVC. Homes were monitored for one week and study participants were asked to rely on mechanical ventilation and avoid window use during the testing. The households were all non-smoking. All homes had a venting kitchen range hood or over the range microwave and bathroom exhaust fans. The dwelling unit ventilation systems complied with California building standards that were based on the ASHRAE 62.2-2010 fan sizing requirements that were current at the time the California standards went in to force. This paper presents summary results of time-integrated formaldehyde, NO_2, and $PM_{2.5}$ measurements together with a summary of home and ventilation system characteristics, CO_2, temperature and humidity. Formaldehyde, NO_2, and $PM_{2.5}$ are the key contaminants of concern in homes with the greatest health impact (Logue et al. (2012)). The results are compared with a prior California New Home Study (CNHS (Offermann (2009))) that monitored pollutants over a 24-hour period in 108 homes built between 2002 and 2004, that did not have whole-dwelling mechanical ventilation.

2 FIELD TESTING

2.1 Diagnostic tests

Air leakage of the building envelope and forced air heating and cooling system was measured with the DeltaQ test (Method A of ASTM-E1554-2013) using a TEC Minneapolis Blower Door System with DG-700 digital manometer. The DeltaQ test determines the air leakage associated with the forced air system at its normal operating conditions, and simultaneously provides the results of a multi-point envelope leakage test that is approximately compliant with the ASTM E779 test method. Airflows of exhaust fans for dwelling ventilation, kitchens and bathrooms were measured using a TEC Exhaust Fan Flow Meter. Kitchen range hood airflows were measured using a balanced-pressure flow hood method described by Walker and Wray (2001). For the range hood test, a calibrated and pressure-controlled variable-speed fan was connected to the underside of the range hood using a custom fabricated transition that was adapted onsite to cover the entire underside of the range hood. Using a pressure sensor, the variable speed fan was controlled to match the flow of the exhaust fan while maintaining neutral pressure between the room and the transition. For microwave range hoods, the top vent was covered with tape to ensure that the airflow measured at the bottom inlet represented the entire flow through the device. Supply ventilation fan flow rates were not measured directly because the air inlets were commonly inaccessible (often mounted on the roof). It was also not feasible to measure flows using in-duct velocity probes because the supply ducts were encased in spray foam insulation in the attic in all four of the HENGH homes that used supply ventilation. It is imperative that during system design and installation that more consideration is given to being able to commission ventilation systems in order to validate their performance and demonstrate compliance with standards.

2.2 Pollutant Monitoring

Pollutants were measured using both integrated one-week samplers and time-resolved (typically 1-minute) devices. Integrated concentrations of formaldehyde and NO_x were measured using SKC UMEx-100 and Ogawa passive samplers. Formaldehyde samplers were deployed in the main living space, master bedroom, and outdoors. $PM_{2.5}$ was measured indoor in the main living space and outdoors. $PM_{2.5}$ integrated filter samples were collected using a co-located pDR-1500 (ThermoFisher) in a subset of the homes and time-resolved photometer data were adjusted using the gravimetric measurements from the filter samples. Time resolved particle measurements were made using photometers (ES-642/BT-645, MetOne Instruments). NO_2 and formaldehyde time-resolved measurements were made using Aeroqual NO_2 monitors and a GrayWolf FM-801, respectively. We also measured temperature, relative humidity and CO_2 outside and in several inside locations using Extech SD-800 and various HOBO monitoring devices. In this paper we focus on the time-integrated pollutant measurements.

2.3 Occupant Activity Monitoring

Cooktop and oven use were monitored using iButton temperature sensors attached to the surface of the cooktop, generally with one iButton adjacent to each burner. The temperature data were analyzed to find rapid increases in temperature that signal use of the cooking appliance. Operation of exhaust fans, range hoods, clothes dryers, and the central forced air system were determined using one of the following methods: a motor on/off senor, air velocity anemometer, or a power meter. The field team determined which method to use depending on the accessibility and configuration of the appliances. Fans with multi-speeds (e.g., a range hood) were monitored using a vane anemometer do detect the operating speed. The air flow at each operating speed was determined separately using diagnostic flow metering. State sensors that discern open vs. closed condition were used to monitor the most often used exterior doors and windows. Although study participants were asked to keep these openings closed during the one-week study period, it was deemed valuable to monitor as any extended natural ventilation could impact pollutant measurements. Temperature and relative humidity were monitored at the supply air registers of the forced air heating and cooling systems as an indicator of heating/cooling use. These data were used as part of the quality assurance procedures when analyzing the pollutant data to determine data anomalies and to check that instruments were responding to events in the home. A full analysis of these data will be published at a later date.

3 RESULTS

3.1 Diagnostics

The measured envelope leakage for most homes was between 3 and 6 ACH50 (Figure 1), with a median value of about 4.5 ACH50. Measured air leakage under pressurization was higher than depressurization by 20% on average. This result is not unusual and is due to "valving" of some envelope leaks, e.g., from an exhaust fan damper being pushed open during pressurization. Only four homes had envelope leakage less than 3 ACH50, the level required for compliance with the 2018 International Energy Conservation Code (ICC 2018) that is used in many construction regulations in the US, but not in California. Median duct leakage was about 50 L/s, with a range from below 10 to over 200 L/s.

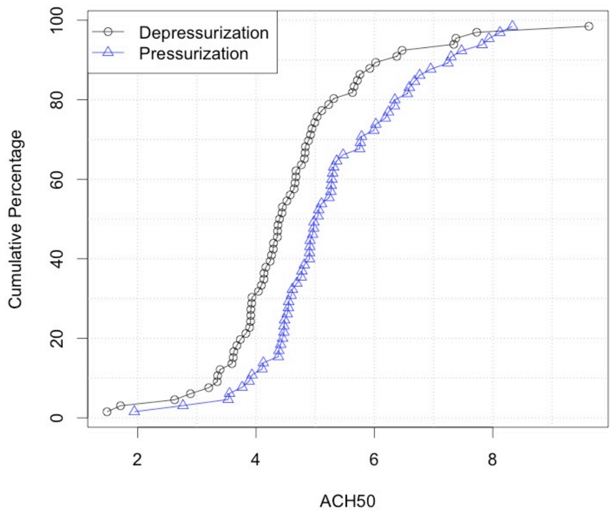

Figure 1: Distribution of Envelope Leakage Measurements

For dwelling unit ventilation, 64 of the 70 homes had exhaust ventilation; the other six had supply ventilation. In all but two cases, the measured flow exceeded the California building standards minimum requirement that is based on the fan sizing requirements in the 2010 version of the US residential ventilation standard: ASHRAE 62.2 (i.e., not taking into account infiltration). This fan sizing requirement was 0.05 L/s/m^2 of floor area plus 3.5 L/s per occupant (assumed to be the number of bedrooms plus one), or about 27 L/s for the average home in this study. The average installed flow was about 50% more than the minimum requirement. This is similar to the results in Stratton et al. (2012) for previous tests of other new (at the time of testing and built in 2010/2011) California homes. It should be noted that the ASHRAE Standard has changed in the intervening years to be a total ventilation rate requirement of 0.15 L/s/m^2 of floor area with the same occupant requirement. For the homes in this study that averaged about 240 m^2 this roughly doubles the total ventilation rate requirement to about 52 L/s, however, using the ASHRAE 62.2-

2016 infiltration credit reduces this to a fan size requirement of about 26 L/s. Therefore, the ventilation systems in these homes are also oversized relative to the newer ASHRAE 62.2 requirements, when infiltration is included. We combined these measured fan flow rates with estimates of natural infiltration to obtain an estimate of overall air exchange rate (AER) for each home. The median AER was 0.35 Air Changes per Hour (ACH). The AER in non-mechanically ventilated homes in the CNHS study were substantially lower, with a median of 0.24 ACH.

On the initial site visit, the mechanical ventilation system was running in 18 homes and the system was turned off in 52 homes. Systems with a label, or less accessible controls were much more likely to be operating. Also, some labels were clearer than others. For example, text stating “Continuous Duty” does not convey information useful to the occupants, resulting in systems being turned off with this style of vague text. A better example of labelling was: “Whole House Ventilation Control. Leave on except for severe outdoor air quality.”. Table 1 presents a summary of the system status when the research team first arrived to the home, by control type and presence or absence of any identifying label.

Table 1: Dwelling Unit Ventilation System Control

System Control	Label	System Status (as-found) - ON	System Status (as-found) – OFF
On/Off Switch	Yes	7	5
	No	2	40
Programmable Controller	No	5	5
Thermostat	No	0	2
Breaker Panel	No	1	0
No Controller	No	3	0
Total		18	52

32 homes had a kitchen range hood and all were able to meet the minimum air flow requirement of 50 L/s, but only 22 of these did so on the quiet low speed setting. 38 homes had over the range microwaves, not all of which were able to meet the minimum air flow requirements and only nine did so at the lowest speed setting. Bathroom exhausts met the minimum air flow requirement of 25 L/s in about 80% of cases.

3.2 Pollutant Measurements

Table 2 summarizes the results of the HENGH study for key pollutants of concern compared to the previous CNHS for homes that were not mechanically ventilated.

Table 2: Median Indoor Pollutant Concentrations

Median Indoor Time-Integrated Concentration	CNHS – 98% Electric No mech vent	HENGH - Gas Homes with 62.2 ventilation
Formaldehyde	30 ppb	18 ppb
PM2.5	10.4 μg/m3	5.0 μg/m3
NO_2	3.2 ppb	4.5 ppb

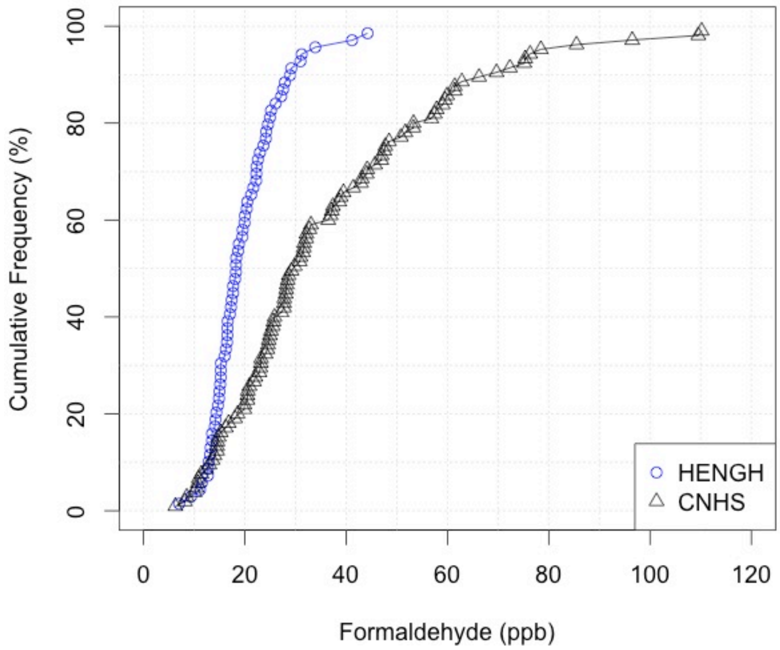

Figure 2: Comparison of HENGH and CNHS Time Integrated Formaldehyde Measurements

In both HENGH and CNHS homes the majority of formaldehyde was from indoor sources (median outdoor concentrations were 2-3 ppb), and HENGH homes had lower indoor formaldehyde compared to CNHS homes, despite being newer when tested (some studies have suggested the formaldehyde concentrations are higher when homes are newer Park and Ikeda (2006)). Figure 2 summarizes the distribution of measured indoor formaldehyde in the two studies. The lower formaldehyde concentrations measured by HENGH in comparison to CNHS may be attributable to California's regulation to limit formaldehyde emissions from composite wood products that came into effect between the two studies. The highest formaldehyde concentration in the HENGH study was 45 ppb, whereas the CNHS had concentrations up to 110 ppb. Almost all homes in the HENGH study exceeded the California OEHHA REL for 8-hour and chronic exposure of 7 ppb, but were below other commonly used reference concentrations for 8-hour and chronic exposure, such as 80 ppb from the World Health Organization (WHO (2010)) and 40 ppb from Health Canada (2006).

Lower $PM_{2.5}$ indoors measured by HENGH compared to CNHS may be explained from a combination of lower outdoor $PM_{2.5}$ levels (6.8 vs. 8.7 ($\mu g/m^3$)), the use of kitchen range hoods, and use of higher efficiency air filters (MERV 11 or better) in some HENGH homes. While 20 of the 67 HENGH homes with outdoor data had outdoor $PM_{2.5}$ exceed the California Environmental Protection Agency annual ambient air quality standard of 12 $\mu g/m^3$, only 12 of the 67 homes with indoor data had indoor concentrations exceed that benchmark.

Gas cooking is a significant source of indoor NO_2 (Mullen et al., 2016). Even though NO_2 concentrations measured by HENGH are similar to levels found in CNHS, the two studies differed in that HENGH homes all use gas for cooking, whereas almost all homes (98%) from CNHS used electric ranges. More analysis is needed to determine the effectiveness of source control, such as range hood use during cooking, on indoor concentrations of cooking emissions such as NO_2 and $PM_{2.5}$. All of the measured NO_2 concentrations were well below the US Environmental Protection Agency 53 ppb annual ambient air quality standard for NO_2.

The median of time-averaged CO_2 concentrations in the HENGH homes was 608 ppm compared to 564 ppm for the CNHS. These results are consistent with the relatively low occupant density in these homes: approximately one person for every 90 m^2. The range of average concentrations for the HENGH homes was lower at 481-770 ppm compared to 405-890 for the CNHS homes. As with the other contaminant measurements (e.g., formaldehyde as shown in Figure 2), the more consistent ventilation provided by mechanical systems makes for less variability in pollutant concentrations – in particular reducing the likelihood of high pollutant levels. In the absence of a consensus limit for CO_2 in residences, we use the ASHRAE Standard 62.1-2016 guideline level of 1100 ppm (700 ppm above the outdoor background of roughly 400 ppm) as a benchmark[1] for CO_2. The highest CO_2 concentrations were found in bedrooms overnight. About 10% of bedrooms had mean CO_2 concentrations overnight in excess of 1100 ppm.

Time-averaged indoor temperature and relative humidity measured in this study were similar to CNHS. The 24 hour time-averaged indoor air temperature results reported for the CNHS study had the same median and mean of 22.4°C, and a range of 17.1 to 28.2°C. The mean indoor air temperatures measured over the roughly weeklong monitoring periods in HENGH homes had the same median and mean of 22.9°C, and a range of 17.8 to 27.1°C. CNHS reported 24-hour average indoor relative humidity with a median of 43%, a mean of 45%, and a range of 20% to 64%. The mean relative humidity measured over the roughly weeklong monitoring periods in HENGH homes had the same median and mean of 45%, and a range of 28% to 60%. Formaldehyde emission rates depend on temperature and humidity. This similarity in indoor conditions indicate that any differences in formaldehyde are due to other factors.

The US DOE Building America program is expanding on the results reported here with a field study performing real-time and integrated pollutant concentrations in about 200 new US homes (in climates other than California). A subset of homes will have measurements with and without ventilation system operation.

4 CONCLUSIONS

The mechanical ventilation systems in the study homes more than met the minimum dwelling unit air flow requirements, and exceed the minimum flows by 50% on average. This indicates that mechanical ventilation systems are being adequately selected and installed by builders of new homes in California. The homes in this study have lower indoor formaldehyde levels than previously measured due to a combination of added mechanical ventilation and, at least in these California homes, as a result of California's formaldehyde emission standards. Indoor concentrations of NO_2 and $PM_{2.5}$ measured are also low compared to a prior study of new homes in California and available standards. In most homes these key pollutants are below levels set for health requirements, or do not exceed the standards by considerable amounts.

[1] ASHRAE 62.1 guideline level of +700 ppm above outdoor background (currently about 400 ppm) is largely based on odor concern in commercial buildings, which is not intended for residences.

Overall, this study has shown that using mechanical ventilation in new homes that meets or exceeds current US standards results in acceptable indoor air quality, and for some pollutants is a significant improvement over homes without mechanical ventilation. For these good results to be achieved it is essential to have well-labelled controls, particularly if the controls are easily accessible, and that systems be designed and installed to allow for air flow measurements for commissioning and performance validation to show compliance with standards.

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