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Mechanical Ventilation and IAQ in Recently Constructed US Homes

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SUMMARY

Data were collected to characterize whole-house mechanical ventilation (WHMV) and indoor air quality (IAQ) in 139 homes across four US regions, including 29 in the Marine climate of Oregon, 26 in Cold-Dry Colorado, 32 in Mixed-Humid Illinois, and 52 in the Hot-Humid Southeast. Thirty-six homes were monitored with and without WHMV operating. All homes had operational cooktop ventilation and bathroom exhaust. Envelope and duct airtightness; mechanical ventilation airflows; time-resolved CO_2, $PM_{2.5}$ formaldehyde and radon; and time-integrated NO_2, NOx and formaldehyde were measured. Participants provided information about IAQ-impacting activities, perceptions and ventilation use. Preliminary results indicate that the installed WHMV often did not meet requirements of ASHRAE 62.2-2010; WHMV was operating in only half of the homes as found and 22% had WHMV airflow at or above the requirement, as found. Homes with WHMV had significantly lower CO2 and radon concentrations compared to those without WHMV running.

KEYWORDS

Field study; fine particulate matter; formaldehyde; carbon dioxide; ventilation standards

1 INTRODUCTION

Indoor air quality is impacted by outdoor pollutants entering with intentional ventilation and uncontrolled infiltration, by pollutants emitted from indoor sources, and by the use of controls including ventilation and filtration. Indoor sources include building materials, furnishings and emissions associated with activities such as cleaning and cooking. High performance residential buildings have airtight envelopes to reduce air infiltration (which reduces outdoor pollutant entry), whole house mechanical ventilation (WHMV) equipment and quiet kitchen and bathroom exhaust fans to help control contaminants from indoor sources. This approach has been widely applied in residential construction codes in the US, through state-specific codes or by adoption of the International Residential Code (IRC). The IRC restricts envelope air leakage to a maximum of three to five air changes per hour at a 50 Pa indoor-outdoor pressure difference (ACH50). Since 2012, the IRC has required WHMV with airflow rates that correspond to those required in ASHRAE Standard 62.2-2010 (ASHRAE, 2010). Standard 62.2 sets requirements for WHMV to provide continuous (or equivalent time varying) ventilation at minimum airflows, sound ratings and availability and labeling of manual override controls, The standard additionally requires an exhaust fan in each bathroom and a kitchen exhaust fan or range hood.

Several papers have reported the impact of WHMV reducing concentrations of air pollutants generated indoors. The recently completed Healthy, Efficient New Gas Homes (HENGH) study of 70 California single family detached houses built since 2011 (Singer et al., 2020) found that homes with mechanical ventilation in line with ASHRAE 62.2–2010 had lower concentrations of formaldehyde (HCHO) and fine particulate matter, and a lower 90th percentile weekly mean carbon dioxide (CO_2), compared to similar homes without WHMV studied a decade earlier. Another recent study of weatherization retrofits of detached homes found decreases in indoor/outdoor concentration ratios for HCHO, CO_2, and PM after retrofits that included exhaust, supply or balanced WHMV compliant with ASHRAE 62.2–2016 (Kang et al., 2022).

The potential for WHMV to control indoor emitted pollutants depends on its capacity and operation. Field studies have found installation, maintenance and operational issues with WHMV systems, including lower installed airflows due to poor installation and maintenance, and less fan operation time due to missing labels, malfunctional controllers or incorrect timer setting (Eklund et al., 2015; Sonne et al., 2015). These resulted in large disparities between design and as-used ventilation airflows for WHMV systems.

This paper presents the methods and preliminary results from a large field investigation supported by the U.S. Department of Energy (DOE) Building America program. Measurements were completed in 139 homes in four regions across five climate zones. Data were collected and analyzed to investigate: (1) whether residential mechanical ventilation equipment is commonly installed correctly and meets the airflow and sound rating specifications of ASHRAE Standard 62.2–2010 and IRC 2012; (2) whether key IAQ parameters differ in homes with and without a WHMV system operating; (3) the impact of controls other than WHMV, including bathroom and kitchen exhaust ventilation and filtration; (4) occupant behavior to operate WHMV and other activities that influence IAQ

2 METHODS

Home recruit and characterization

The study focused on single-family homes built in 2013 or later without smoking inside. The study was implemented in four areas: the Marine climate of the Pacific Northwest (Oregon), the Cold-Dry climate of the Mountain region (Colorado) during generally colder months, the Hot-Humid climate of the Southeast (mostly in Florida) and the Mixed-Humid/Cold Midwest (central Illinois). The intent was to achieve samples in each area that included roughly an even split of homes with and without WHMV. Participants agreed to not substantially use natural ventilation and to not change the WHMV setting (on or off) prescribed for the monitoring period. Field research teams conducted measurements and observations of ventilation equipment characteristics and settings and asked residents about the equipment present and their understanding of how to use it. Duct and envelope leakage and ventilation fan airflows were measured. Occupants were requested to take an online IAQ survey and record their daily activities.

Cooking appliance and ventilation equipment monitoring

Cooking burner use was monitored with iButton temperature sensors placed on the cooktop surface adjacent to each burner and at the oven vent. Operation of WHMV systems, exhaust fans, range hoods, clothes dryers, and the CFA system was monitored with data-logging vane anemometers, sensors for motor on/off or plug-through power meters. Magnetic state sensors were used to monitor the most often used exterior doors and windows. Other cooking appliances and air cleaner usage was measured by a plug-load energy meter if present.

Time-resolved and passive indoor air pollutants measurements

Air pollutant concentrations, temperature and humidity were measured at one outdoor and up to three indoor locations (Table 1). All parameters were measured at a central indoor location, e.g., a living room, dining room or large, open "great room" that typically included the kitchen. Several parameters also were measured in the master bedroom and at a third location such as an office or family room. Radon concentration was measured at the lowest occupied level of the house.

Table 1. Air quality measurement devices, parameters, and sampling locations.

Measurement Device	Parameters	Accuracy[1]	Res.	Sampling locations
Met One ES-642 Photometer	Estimated $PM_{2.5}$ by photometry	±5% traceable standard with 0.6 µm PSL, autozeroing function enabled to check baseline hourly[2]	1 min	Outdoor
Met One BT-645 Photometer	Estimated $PM_{2.5}$ by photometry	Same as above.	1 min	Indoor central
AirVisual Pro	Estimated $PM_{2.5}$ by photometry, CO_2, T, RH	CO_2: ±50ppm or 2% of reading PM: Within 10% in effective range: 0–1798 µg/m3	10 sec	Indoor central; Main BR; Other (office, bedroom or family room
Ogawa Passive Samplers	NO_2 and NO_x	Based on field validation: 7 d relative deviation of 3±2% NO_2 at 11-37 ppb; 4±3% NO_X at 16-85 ppb; 10±9% (NO_X-NO_2) at 4-56 ppb	1 wk	Outdoor; indoor central
GrayWolf FM-801	HCHO	±4 ppb <40 ppb, ±10% of reading ≥40 ppb	30 min	Indoor central; Master BR
SKC UMEx-100 Passive	HCHO	±25%, exceeds OSHA requirements	1 wk	Outdoor; Indoor central, Master BR
Onset HOBO UX100-011, U23 Pro v2	T, RH	±0.21 °C from 0 to 50 °C ±2.5% from 10% to 90%; up to ±3.5% at 25 °C including hysteresis	1 min	Outdoor (U23); Indoor central (UX100-011);
RadStar RS300	Radon	<10% deviation from 0.5 to 150 pCi/L	60 min	Indoor: central and/or basement

Preliminary data analysis

Collected data were reviewed and time series data were resolved to 1-min averages and combined into a single data sheet for each sample week. The minute-by-minute total air change rate per hour for each home was estimated by a combination of the various mechanical ventilation systems, duct leakage flow and natural infiltration due to stack and wind effects and envelope leakage, as described in the ASHRAE Fundamentals Handbook (ASHRAE, 2021). The outcomes of calculated ACH and various IAQ parameters were analyzed by groups defined by the presence and operation of WHMV during the measurement period. WHMV operation was evaluated by comparing the calculated continuous or average hourly mechanical airflow to the requirements of the IRC (2012) or ASHRAE 62.2-2010. Homes with at least 80% of required airflow were considered as having an WHMV and homes with no more than 20% of required airflow were counted as having no WHMV. The IAQ and other parameters comparison were conducted with Wilcoxon matched-pairs signed-rank test.

3. RESULTS and DISCUSSION

The paper presents preliminary results as data analysis is still ongoing, with more results available in the future. Results are provided here for home characteristics, overall WHMV configurations results in homes and preliminary indoor pollutants results.

Collected homes and building characteristics in study area

A total 139 homes were studied, including 29 homes in the Marine climate of Oregon, 26 homes in the Cold-Dry climate of Colorado during generally colder months, 52 homes in the Hot-Humid climate in the southwest US (most in Florida) and 32 homes Mixed-Humid Illinois. Thirty-nine homes (8 in OR, 8 in CO, 12 in SE US and 8 in IL) were monitored over two weeks: one week with WHMV operating and one week without WHMV operating. The general building characteristics of homes in each studied region compared to HENGH homes in California are shown in Table 2.

The homes in all regions in this study had similar age compared to HENGH homes. Study homes in California, Colorado and Illinois were larger than Oregon and southeast homes, but the density were similar except Colorado homes. Similar to CA homes, most homes in OR, CO and IL had gas appliances but there are fewer homes in the southeast US that had gas burners. Forty percent of the tested homes in IL were not equipped with a venting range hood.

Table 2. Home characteristics in each study region and compared to HENGH homes in CA, Values are median (10th–90th) unless specified

	California (70)	Oregon (29)	Colorado (26)	Illinois (32)	FL/GA/SC (52)
Year built, Median (range)	2014 (2011–2017)	2016 (2013–2018)	2015.5 (2013–2018)	2016 (2013–2020)	2017 (2013–2020)
Floor area, sf	2616 (1572–3649)	2164 (1594–3289)	2825 (1850–4139)	2721 (1492–3846)	2146 (1425–3397)
1 / >1 stories (#)	27 / 43	1 / 28	6 / 20	14 / 16	33 / 17
Residents	3 (2–5)	3 (2–4)	2 (2–4)	4 (2–5)	3 (2–5)
Density, sf/person	828 (484–1539)	900 (589–1519)	1225 (751–2175)	758 (456–1380)	847 (500–1686)
Envelope leakage, ACH50	4.4 (3.4–6.0)	2.9 (1.9–5.0)	2.8 (2.0–4.3)	3.5 (1.7-5.3)	3.8 (1.9–5.7)
Gas cooktop/oven	100% / 43%	90% / 40%	88% / 38%	70% / 70 %	47% / 25%
Vented kitchen exhaust	100%	100%	100%	60%	84%

WHMV configuration

Similar to California homes in the HENGH study, the exhaust fan was the most common WHMV found in Colorado and the Southeast. In Oregon, supply ventilation systems were more common (i.e. CFIS) in homes. In the hot-humid southeast, a few homes had ventilating dehumidifiers as supply ventilation to control the indoor humidity. Out of 32 homes in Illinois, 22 did not have code-required WHMV equipment, and nine homes had a CFIS.

Table 3. WHMV system type in homes

WHMV Type	California (70)	Oregon (29)	Colorado (26)	Illinois (32)	FL/GA/SC (52)
No WHMV equipment	0	5	1	22	5
Uncontrolled CFIS[a]	0	0	1	0	5
HRV/ERV	0	3	4	1	6
CFIS with controller	2	14	0	9	6
C-CFIS with supply fan	4	0	1	0	0
Ventilating dehumidifier	0	0	0	0	5
Integrated CFIS + continuous exhaust	0	3	0	0	1
Exhaust fan(s)	64	4 (1 with U-CFIS)	19 (5 with U-CFIS)	0	24 (4 with U-CFIS; 4 with C-CFIS)

[a] Uncontrolled CFIS are never compliant as WHMV by 62.2 or IECC

The overall in-home performance of the WHMV system was found to be far below the building code requirement. Almost half of the homes (49 out of 106) with any type of WHMV including uncontrolled CFIS were found not operating their WHMV during the first arrival of the field team. Those homes were mostly found in the southeast US, with only 32% of homes with a WHMV operating as found. Among the 57 homes that were operating WHMV in some manner, less than half of them had installed airflow and runtime to meet the minimal requirements of ASHRAE 62.2-2010. In homes in which the WHMV was not operating or operating with airflow below the 62.2 requirement, the field team tried to increase runtime and/or airflows to achieve the required airflow. Even with these efforts, the WHMV in 43 of 99 (43%) homes couldn't meet the minimum airflow requirements of 62.2.

Table 4. WHMV system as found and capable performance

Region (Total homes)	Oregon (29)	Colorado (26)	Illinois (30)	FL/GA/SC (52)
Any type of WHMV including uncontrolled CFIS	24	25	10	47
WHMV airflow not determined	6	1	0	1
Operating in some matter as found	15 (+4 unclear)	21	6	15 (+1 unclear)
Operating at ≥100% 62.2-2010 as found	7 of 15	13 of 21	0	3 of 15
Capable of ≥100% of 62.2 by adjustment (among homes with systems with measured airflows)	15 of 18	16 of 24	2 of 10	23 of 47
WHMV airflow >80% of 62.2 during sampling week(s), including 2-week	11	19	8	23

IAQ in homes with and without WHMV

Preliminary results of indoor air pollutants concentrations measured in two-week homes with and without WHMV operating are shown in Table 5. Radon concentrations measured at the lowest level indoors and the CO_2 concentrations measured both at central indoor locations and master bedrooms were found to be significantly lower during the weeks with WHMV operating compared to weeks without WHMV. Though overall $PM_{2.5}$ concentrations were not significantly different between WHMV on and off weeks, preliminary results in Colorado and Portland homes found a larger PM decay rate in homes with WHMV (Antonopoulos et al., 2023). No significant differences in HCHO concentrations were observed between homes with and without WHMV. While substantially increasing ventilation in an individual home is expected to reduce formaldehyde in that home, ACH may not be the dominant factor impacting concentrations across homes. This is because formaldehyde emissions vary by home and by environmental conditions.

Table 5. Indoor and outdoor formaldehyde, radon, $PM_{2.5}$ and CO_2 concentrations in two-week homes with and without WHMV; concentrations are shown as weekly median (10th –90th)

	CO+OR n=16		Central IL n=8		FL/GA/SC n=12	
Pollutant location	<20% WHMV	>80% WHMV	<20% WHMV	>80% WHMV	<20% WHMV	>80% WHMV
HCHO, Outdoors	1.5 (1.2–2.8)	2.1 (1.3–3.4)	1.3 (0.9–2.4), n=7	1.5 (1.1–2.6)	2.6 (2.0–3.8) n=8	3.3 (1.8–4.8)
HCHO, Central Indoors	23 (16–41)	25 (19–37)	19 (14–31), n=7	21 (13–28)	28 (19–43) n=11	28 (17–40)
Radon, Indoors	0.42* (0.26–1.9) n=13	0.30* (0.11–1.5)	0.35* (0.19–3.96)	0.29* (0.15–3.11)	1.3* (0.6–1.8)	0.7* (0.5–0.9)
Optical $PM_{2.5}$, outside	4.3 (2.2–6.7)	3.0 (2.2–6.5)	4.9 (2.2–8.7)	4.7 (2.1–6.3)	5.1 (4.3–6.3)	5.2 (3–7.6)
Optical $PM_{2.5}$, inside	2.7 (1.3–6.8)	1.9 (0.9–3.6)	2.8 (1.2–13.8)	2.9 (1.4–6.0)	2.6 (1.7–5.7) n=11	3.3 (1.7–6.9) n=11
CO_2, Central Indoors	692* (535– 947)	577* (497 - 696)	702* (607–876)	585* (523–765)	887* (460–1223)	594* (492–931)
CO_2, bedroom	828* (575–1066)	666* (526–785)	922* (722–1131)	761* (591–983)	915* (602–1183)	647* (534–902)

* Significant difference were found between groups with/without WHMV at $P<0.05$ using Wilcoxon matched paired test

4 CONCLUSIONS

Field investigation in 139 recently built homes across four different regions in the US found the installed performance of WHMV systems were often lower than ASHRAE 62.2-2010 requirement, though all homes were built with the requirement to have WHMV meet standard. About half of the homes did not run the WHMV as found and only 22% of the homes had WHMV as found above 62.2 requirements. The installed capable airflow of

WHMV was found much lower compared to device design airflows. Significant differences in CO_2 and Radon concentrations were found in homes with and without WHMV operating.

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