Rethinking Occupancy-Based Ventilation Controls

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ABSTRACT

Traditionally, occupancy-based ventilation controls have only ventilated when occupants are present – usually based on measurements of CO_2 and/or humidity. These indictors may be fine for pollutants released directly by occupants, such as bioeffluents, or by their activities, such as cooking and cleaning. However, they do not account for pollutants not associated with occupancy, such as formaldehyde from building materials and furnishings. In this study we examined how occupancy-based ventilation controls could account for these other pollutants using the relative exposure approach for variable ventilation. A real-time control was used for exhaust and balanced fans, three occupancy schedules and two different pollutant emission assumptions using the REGCAP ventilation and residential energy simulation program. The simulations were performed for a prototype high performance home compliant with U.S. Department of Energy Building America Zero Energy Ready program requirements in the 15 climate zones defined by the U.S. DOE. Median ventilation energy savings were between zero and 26% of ventilation-related energy use depending on the occupancy schedule, climate, fan type and emission assumptions. Occupancy-based control savings increased for balanced ventilation fans, reduced emissions during unoccupied periods, and longer unoccupied times. Accounting for pollutant emissions during unoccupied times significantly reduces the energy savings for occupancy-based controls.

KEYWORDS

Ventilation, controls, occupancy, emissions, energy

1 INTRODUCTION

While residential smart ventilation controls (SVC) that maintain equivalence with ventilation standards are a relatively new concept, the notion of controlling ventilation airflows based on occupancy is well established and relatively commonplace in commercial and institutional buildings. Typically, this is referred to as demand controlled ventilation (DCV), and it relies on measurement of carbon dioxide (CO_2) concentrations and/or relative humidity in the occupied space. This strategy implicitly assumes that either: 1) carbon dioxide and other human bioeffluents are the only pollutants that need to be controlled, or 2) all other sources of indoor pollutants are correlated to occupancy. Systems are controlled to a low level or turned off completely during unoccupied periods, which allows the build-up of contaminants that are not bioeffluents or related to human activity in the space (e.g., formaldehyde, many VOCs, contaminants of outdoor origin, etc.). For example, Hesaraki & Holmberg (2015) showed that for unoccupied periods exceeding 4-hours in a new home, VOCs rose to unacceptable levels. In their review of CO_2-based DCV, Emmerich & Persily (2001) underline the limitations inherent in using CO_2 because of its inadequacy as an overall indicator of IAQ, especially for pollutant emissions from sources other than occupants, such as building materials and furnishings. In addition, some contaminants related to human activities can be emitted in the home when occupants are no longer present, e.g., cleaning chemicals and their reaction offspring (Destaillats et al. (2005)). The main objective of this work was to account for pollutants emitted when dwellings are unoccupied in occupancy-based ventilation controls.

The ventilation strategies explored in this study used real-time IAQ ventilation controls based on relative dose and exposure. These controls are an implementation of the equivalent ventilation principle (Sherman et al. 2011a; and Sherman et al. 2012) that allows a time-varying ventilation rate to give the same dose and exposure to a generic continually emitted pollutant as a continuously operating constant ventilation rate. Our controls use the same relative exposure calculations found in ASHRAE Standard 62.2-2016 (ANSI/ASHRAE (2016)), based on original work by Sherman et al. (2012). Note that the ASHRAE Standard, and our simulations, assume that kitchen and bath fans are used as source control to remove contaminants related to cooking and bathing (i.e., moisture, odour and cooking byproducts , such as NO_2, particles, VOCs).

This study builds on this previous work by using simulations to develop real-time control strategies based on relative dose and exposure to examine the potential energy savings based on changes in ventilation when a home is unoccupied. These control strategies calculate a relative dose and exposure based on continuously emitted pollutants and a time-varying ventilation rate, and they control the dose and exposure such that the annual average is less than or equal to one (i.e., the same exposure as for a continuously operating ventilation system). This study also included simulations where emissions are reduced to half the occupied rate when unoccupied.

2 SIMULATIONS

The REGCAP simulation tool was used to predict the ventilation and energy performance. It combines detailed mass-balance models for ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. The details of this model have been presented elsewhere (Walker, 1993; Walker & Sherman, 2006; Walker, Forest, & Wilson, 2005), along with validation summaries of house and attic air, mass and moisture predictions. REGCAP is implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance and to allow for dynamic time-based controls. REGCAP combines natural infiltration with mechanical air flows from the house ventilation system that is the subject of the ventilation controls, as well as kitchen, bathroom and dryer exhausts flows.

All simulations used a single-story, 200 m^2 (2,153 ft^2) home with three bedrooms, two bathrooms and four occupants. The homes are compliant with the energy and performance specifications of the U.S. DOE Zero Energy Ready Home program. These include thermally efficient envelopes (RSI 2.3-4.43 walls), high performance HVAC equipment (80 to 94 AFUE heating, SEER 13 to 18 cooling) and airtight construction (1.5 to 3 ACH_{50}), with the various performance requirements varying by US DOE climate zone. All DOE climate zones 1-8, including marine, moist and dry were simulated—15 in total. Three idealized occupancy patterns were simulated: (1) 1st shift was unoccupied from 8 am to 5 pm on weekdays, (2) 3rd shift was unoccupied from 9 pm to 6 am on weekdays, and (3) an extended 1st shift pattern was unoccupied from 8 am to 10 pm, with two additional two-hour absences each weekend day. All scenarios were run with both an exhaust and a balanced IAQ fan. Exhaust fan cases were tested with two pollutant emission assumptions: (1) fullAEQ, assumes continuous emissions every hour of the day, and (2) halfAEQ, assumes emissions are cut in half during unoccupied periods. The auxiliary fan operation aligned with mealtimes and sleep hours with: 40 minutes per day clothes dryer (71 L/s (150 cfm)), 40 minutes per day kitchen fan (10-min breakfast and 30-min dinner events, 47 L/s (100 cfm)), and four 20-minute bath fan events (24 L/s (50 cfm)). The air flows from the auxiliary fans are included in the calculations of ventilation rate for the home but are not included in the control systems or in estimates of relative dose and exposure. More details on these simulations can be found in Less and Walker (2018).

In each scenario, we simulated two baseline (no ventilation controller) cases: (1) with no IAQ fan, and (2) with a minimally compliant, continuous fan sized to meet the ASHRAE 62.2-2016 ventilation standard. The energy attributed to meeting the ASHRAE ventilation standard was the difference in total annual HVAC energy consumption between these two cases. The energy savings for occupancy-controlled cases were calculated by subtracting the total HVAC energy consumption for the smart control cases from the ASHRAE 62.2-2016 baseline. Fractional ventilation energy savings were calculated by dividing the savings by the energy required to meet the ASHRAE standard.

The smart control cases must have larger IAQ fans than the continuous fan baseline cases. When the ventilation rate is reduced during unoccupied hours, the relative exposure increases, and a larger fan is needed to reduce it back below one when occupants return home. In this study, we have over-sized the ventilation fans by a factor of two. For longer absence times (1st shift extended), this was not sufficient and controllers failed to maintain annual equivalence during occupied hours, so we increased fan over-sizing to a factor of 2.5 for those cases.

2.1 Real-time Control Strategies

The basis of real-time control is to calculate relative dose and exposure periodically, based on the combined infiltration and mechanical fan airflows. In these simulations we used a calculation time period of one minute. This captures the operation of the auxiliary fans and allows for short time scale operation of the ventilation system. The control turns on the ventilation system when either relative dose or exposure are greater than one during occupied periods. This approach has been used previously in the “RIVEC” controller developed by Sherman & Walker (2011) and Turner et al. (2014). To avoid short cycling (that in a real system would lead to poor fan longevity), the decision to turn the ventilation fan on or off is made every ten minutes. When the home is unoccupied, the controller turns on the ventilation system when relative exposure is greater than five, as required by ASHRAE 62.2-2016 and is based on the acute to chronic concentration ratios for pollutants of concern (Sherman et al. (2011b) and Sherman et al. (2012)). This is done to avoid acute exposures upon occupants returning to the home. During unoccupied periods, the relative dose is no longer calculated, and is fixed at its last occupied value. Exposure continues to be calculated during both occupied and unoccupied periods. When occupants return home, relative dose is calculated again and rises above one in response to the high relative exposure (up to 5). The controller must then bring relative exposure and relative dose below one by ventilating the house at a higher rate. We refer to this as the ‘recovery period’. The duration of the recovery period is dependent on the ventilation system air flow, unoccupied duration, and natural infiltration rate.

3 RESULTS AND DISCUSSION

The median air exchange rates and relative exposures calculated over all climates and occupancy patterns are summarized in Table 1. Occupancy controls save energy by reducing the overall ventilation rate, while maintaining equivalent exposure during occupied hours. The best controllers will use the least airflow to provide equivalent occupied exposure. These results show that the occupancy controls reduced the air exchange rates relative to the baseline cases, by between 4 and 12%. For comparison, a traditional DCV control that simply turns the fan off while unoccupied would reduce ventilation by roughly 38% (9-hours / 24-hours). Reductions in air exchange were greatest in cases where emissions are reduced during unoccupied times. For all smart control scenarios, the relative exposures for occupied periods are less than or equal to one – showing that these controls are effectively controlling exposure and demonstrating compliance with the ASHRAE 62.2-2016 ventilation standard. Low ventilation and high exposure occurs in the unventilated case that was run to isolate the energy use due to ventilation the air exchange.

Table 1: Median values for annual average air exchange rate and relative exposure.

Case	Fan Type	Unoccupied Emissions	Air Exchange (ACH)	Relative Exposure
No IAQ fan	None	Full	0.102	4.959
Baseline	Exhaust	Full	0.340	1.005
	Balanced	Full	0.358	0.999
Occupancy controller	Exhaust	Full	0.326	1.001
	Exhaust	Half	0.298	0.996
	Balanced	Full	0.328	1.007

Figure 1 shows the ventilation energy savings for each combination of climate zone, occupancy pattern, and combination of fan type and emissions assumptions. Median ventilation energy savings across climate zones varied from 0 to 26% depending on fan type and emission assumptions. Overall, ventilation energy savings are quite low for occupancy-based smart ventilation controls, with some 1st shift exhaust fan full emission cases even increasing energy consumption. Savings increased somewhat for the balanced fan cases and for the cases where emissions were halved during unoccupied periods. Savings are higher in the 3rd shift vs. the 1st shift occupancy pattern. The extended 1st shift pattern has the greatest savings of all, showing that greater unoccupied periods lead to increased savings. The greatest percent savings are in the hot climates (DOE CZ 1 and 2), while all other climate zones have fairly consistent percent savings.

These results can be explained by considering diurnal temperature patterns and their correlation with occupancy. Overall, the 3rd shift pattern had increased energy savings, because the ventilation fan is turned off during cold nighttime hours, whereas the 1st shift pattern turns the fan off during the mildest daytime hours. The 3rd shift pattern then has increased ventilation during mild daytime hours, while the 1st shift has increased ventilation during the cold evening and nighttime hours. These patterns provide a predictable heating benefit in the 3rd shift and a heating penalty for 1st shift. The opposite is true of cooling, where the 1st shift pattern provides a notable benefit. This cooling benefit in the 1st shift is why savings were highest in the cooling dominated locations.

Relative to the exhaust fan cases with full emission rates, both the balanced fan cases and the half emission rate cases had greater reductions in the average ventilation rate and increased energy savings. Balanced fan airflows add linearly to natural infiltration (exhaust fans are sub-additive), which means they provide increased ventilation rates, but they also provide greater decreases in ventilation when turned off by a smart controller. The increased impact of turning off a balanced IAQ fan led to greater reductions in airflow and increased energy savings. The half-emission scenarios also reduced the total airflow required to maintain equivalent exposure during occupied periods, because the peak exposure to the occupants was reduced, and the duration of the over-ventilation recovery period was less than with the higher emission assumption. This reduced recovery period is illustrated in Figure 2 where we see that the recovery period of increased ventilation is cut more than in half, as is peak exposure.

Martin et al. (2018) reported similarly low energy savings from EnergyGauge simulations of occupancy-based ventilation controls, at 28 kWh/year (1% of consumption). They noted that savings were limited due to low thermal loads during the daytime hours when the home was unoccupied, as well as to the small differences in whole house airflows when the exhaust fan was on vs. off, due to sub-additivity of exhaust fans with natural infiltration. Walker et al. (2017) estimated that DCV technologies can save anywhere from 0 to 60% of ventilation energy use, based on an exhaustive review of 38 studies in residences dating back to the 1980s. They note that differences in smart controls, reference cases and metrics limit the ability of compare between studies.

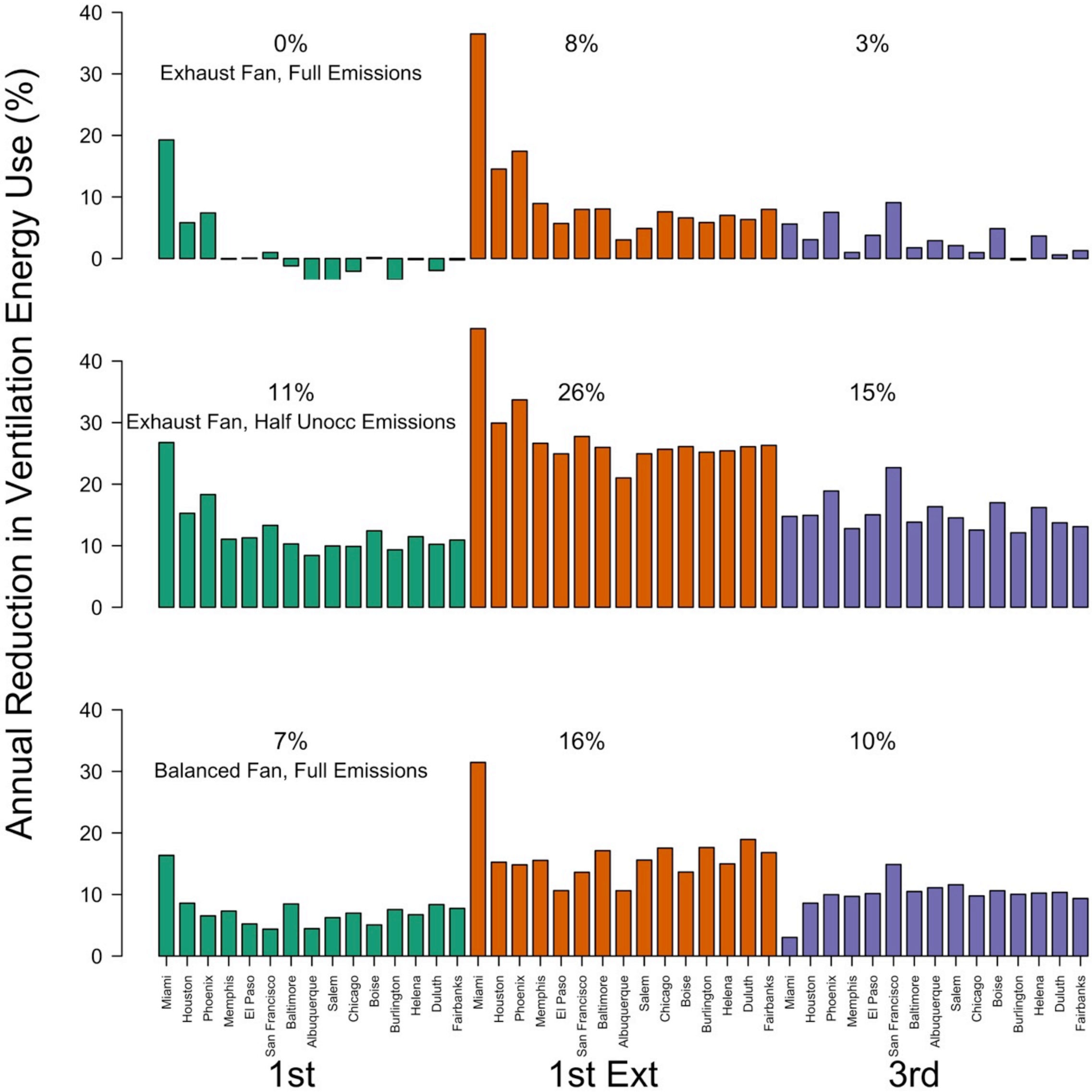

Figure 1: Annual percent reduction in the ventilation energy use for each climate zone, occupancy pattern and combination of fan type and emission assumptions. Median savings indicated for each category.

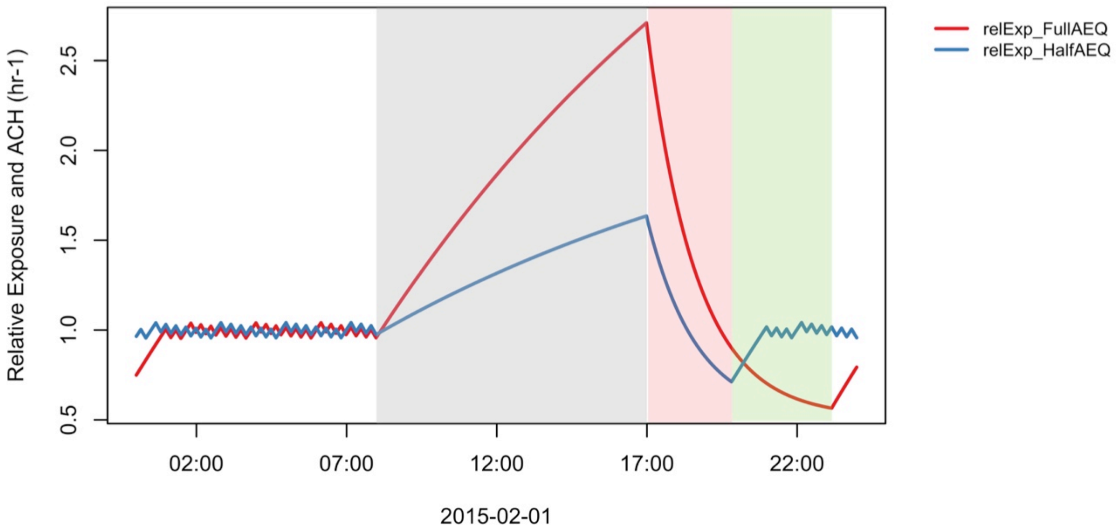

Figure 2: Time-series plot of relative exposure in a Baltimore home, comparing the recovery period with full emissions (fullAEQ, red line) and emissions that are halved during unoccupied periods (halfAEQ, blue line). Unoccupied period highlighted in grey, Half AEQ recovery period in pink, and Full AEQ recovery period in green.

4 CONCLUSIONS

Traditionally, occupancy controlled ventilation systems simply turn off ventilation during unoccupied times to achieve energy savings. However, this fails to account for pollutants emitted during those unoccupied times (e.g., formaldehyde from building materials and furnishings). This study used equivalent exposure-based smart ventilation controls to include pollutants emitted during both occupied and unoccupied times to ensure that occupant exposure was the same as for a system that continually ventilated the home. This is an important issue because saving energy by increasing exposure is not an acceptable energy savings strategy. Simulations across a wide range of climates showed that accounting for pollutants emitted during unoccupied periods drastically limited the reductions in average ventilation rate to between 4 and 12%, compared with the theoretical 38% reduction from turning a ventilation fan off for nine out of 24-hours. As a result, ventilation energy savings were small for occupancy-controls that account for emissions during unoccupied hours. This implies that future research should investigate the difference in pollutant emissions between occupied and unoccupied times.

Savings varied by occupancy pattern, with increased savings if the home is unoccupied at night due to diurnal patterns of outdoor temperature. More unoccupied hours led to greater savings. For the most common occupancy pattern, where the home is unoccupied during normal working hours, average savings over all climates was close to zero for an unbalanced fan and 7% for a balanced system. Cooling dominated locations had the highest fractional savings. Balanced fans had increased energy savings, due to their direct additivity with natural infiltration. Similarly, scenarios that assumed pollutant emissions were cut in half during unoccupied times had increased energy savings to an average of 11% for a typical occupancy pattern.

5 ACKNOWLEDGEMENTS

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