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Smart Ventilation Control of Indoor Humidity in High Performance Homes in Humid U.S. Climates

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ABSTRACT

Elevated indoor humidity levels in homes represent a risk to occupant thermal comfort and health, as well as building durability. The improved thermal properties of high performance homes lead to less cooling system run time and associated moisture removal. High performance homes often have elevated indoor humidity, as a result. Current technologies for addressing this high humidity include dehumidifiers, energy recovery ventilators and enhanced cooling strategies. A strategy that has not been assessed to-date is the smart control of ventilation systems to better manage indoor moisture and reduce humidity loads. Such smart controls time-shift ventilation to reduce the duration and number of hours of high indoor humidity, while providing annual pollutant exposure equivalent to a continuously operated fan sized to ASHRAE Standard 62.2-2013. The REGCAP simulation tool was used to assess 13 smart ventilation control strategies. Elevated indoor humidity was mostly problematic only in smaller homes with higher moisture gains. The best controls were able to achieve significant reductions in indoor humidity without excessive energy penalties (e.g., 16% of annual hours reduced below 60% RH in a small Miami home, using 277 kWh annually). They also maintained equivalent air quality to a continuous 62.2-2013 fan. In the cases with highest indoor humidity, smart ventilation controls did not eliminate the need for supplemental dehumidification, with 20 to 25% of annual hours remaining >60% RH.

INTRODUCTION

High relative humidity (RH) levels have been documented in mechanically vented, high performance homes in monitoring studies (e.g., Rudd and Henderson, Jr. 2007), as well as predicted in building simulations (Lstiburek et al. 2007; Martin 2014; Walker and Sherman 2007; Rudd et al. 2013; Fang, Winkler, and Christensen 2010). In standard (non-high performance) homes, indoor humidity is kept at least partially in-check by operation of the central cooling system and its associated moisture removal. The improved thermal properties of high performance homes lead to less cooling load and less associated moisture removal. While ventilation is often cited as a contributor to higher indoor RH in high performance homes in hot-humid climates (where outside air can at times be more humid than inside), it is a secondary factor along with home moisture capacitance. Primary factors include varying internal moisture generation rates, sensible gains (as they impact cooling system runtime), thermostat set points and duct location (Henderson and Rudd 2010). The impact of ventilation on humidity levels in high performance homes is unclear, because the effects depend on many other factors, though some have suggested that mechanical ventilation clearly contributes to high humidity during shoulder seasons.

Simulation efforts and field studies have described and assessed the costs and effectiveness of strategies to reduce indoor humidity levels in high performance, humid climate homes (Kerrigan and Norton 2014; Rudd and Henderson, Jr. 2007; Withers and Sonne 2014). The main goal of these efforts was to reduce the number of hours above 60% RH to an unspecified, "acceptable" level. Strategies have included: Dehumidifiers, including stand-alone and integrated with ventilation and central HVAC systems, energy recovery ventilators, and enhanced cooling strategies (e.g., reduced airflow per ton, sub-cooling of space and sub-cooling plus reheat).

Key findings from this past work include: High indoor humidity generally does not occur during cooling system operation and most problems occur during winter and shoulder season transitions or during late evening and early morning hours; Internal moisture generation has a strong impact on indoor humidity; Sensible cooling load drives cooling system moisture removal, in particular duct location (house vs. attic) and thermostat setting; Mechanical ventilation has non-negligible but secondary impacts on indoor humidity levels; Supplemental dehumidification is required in high performance homes in humid climates, irrespective of mechanical ventilation rates; Homes using supplemental dehumidification strategies are able to reduce, but not eliminate hours of indoor relative humidity above 60% (on average from around 30% of annual hours to 15% of hours >60%; dehumidifier capacity and set points

interact such that all high humidity hours are not eliminated). Supplemental humidity control strategies have mixed effectiveness and first costs from $150 to $2,000 (Rudd 2013a; Kerrigan and Norton 2014). Rudd (2013a) estimated that supplemental dehumidification in high performance homes requires approximately 170 kWh per year with a 60% RH set point (five times that with a 50% RH set point), and Kerrigan and Norton (2014) estimated that dehumidifiers operate 10% of the year in high performance homes with annual energy use of 976 kWh/year. Field research in conventional homes suggests that dehumidifiers use between 300 and 2,000 kWh annually, averaging 1,000 to 1,200 kWh per year (Mattison and Korn 2012; Whitehead et al. 2013).

The current study used simulations to examine several approaches to smart ventilation controls aimed at improving humidity control. The ventilation strategies were evaluated in several climates, house sizes and moisture generation rates to ensure that recommended strategies have robust performance across a wide range of homes. The performance of each control strategy was determined by comparing to baseline simulations with a constant fan.

SMART VENTILATION CONTROLS

Smart ventilation strategies have been previously applied to energy conservation and peak demand reduction using time-based controls and sensors for other ventilation fans (Sherman and Walker 2011), and based on indoor/outdoor temperatures (Less, et al. 2014). The same principles will be applied in this study for humidity control.

The objectives of the smart ventilation control strategies were to reduce the number of hours of high indoor humidity, while avoiding excessive energy use and maintaining acceptable IAQ. "Excessive energy use" is defined relative to the energy use of other means of providing moisture control in high performance homes, namely supplemental dehumidification (roughly 1000 kWh/year). "Acceptable IAQ" is defined as providing annual pollutant exposure equivalent to a continuously operated ventilation fan sized to ASHRAE Standard 62.2-2013. Recent work has developed the concept of ventilation equivalence (Sherman et al. 2012; Sherman et al. 2011), which can be used in smart controls to ensure that variable ventilation rates give the same pollutant exposures as constant ventilation rates. Equivalence is assessed relative to a generic pollutant generated indoors at a constant rate—indoor moisture is not the pollutant considered in the equivalence calculations presented in this work. Equivalence allows a controller to change the time that ventilation occurs to better control indoor humidity. Annual equivalence is determined using real-time calculations of turnover, relative exposure and relative dose (see Equations 1, 2, and 3 below)—relative dose is roughly the relative exposure over a 24-hour integration time. Dose and exposure equal one when ventilation is equivalent to a continuous fan sized to ASHRAE 62.2-2013. Values greater than one mean dose and exposure are higher (worse IAQ), and values below one mean dose and exposure are reduced relative to a constant 62.2 fan (better IAQ). In order to avoid acute exposures, the smart controllers developed in this study used real-time relative exposure and dose calculations to limit relative exposure to a maximum of 2.5 (i.e., pollutant exposure roughly two-and-a-half times the reference case). This is considered a conservative, protective value for 24-hour calculation periods, based on an assessment of the ratios of acute-to-chronic health-based exposure limits (Sherman et al. 2011).

$$\tau_i = \frac{1-e^{-A_i \Delta t}}{A_i} + \tau_{i-1} e^{-A_i \Delta t} \tag{1}$$

τ_i = Turnover at time-step *i*
τ_{i-1} = Turnover at the previous time-step, *i-1*
A_i = Air exchange rate at time-step *i*, hr^{-1}
Δt = time-step, *1/60 hours*

$$e_i = A_{eq} t_i \quad (2)$$

e_i = Relative exposure at time-step i
A_{eq} = Target steady-state ventilation rate (Q_{tot} from ASHRAE 62.2-2013 Equation 4.1b), hr^{-1}

$$d_i = A_{eq}\tau_i(1-e^{-\Delta t/24hrs}) + d_{i-1}e^{-\Delta t/24hrs} \quad (3)$$

d_i = Relative dose at time-step i

In addition to time varying ventilation, this study also investigated the influence of ventilation system design by including systems that tied operation of the ventilation system to operation of the cooling system (that includes incidental dehumidification). Six climates (Miami, Houston, Orlando, Memphis, Charleston and Baltimore) were selected to represent a range of climates that include locations where outdoor humidity is high year-round (Miami) and ones where outdoor humidity is only high in summer (Baltimore). TMY3 data were used in this humidity analysis. Daily and hourly variations in outdoor humidity were found to be progressively smaller than the monthly seasonal variation by factors of about 3 and 4-9 respectively, indicating that there is more to be gained by ventilation timing strategies that are seasonal.

Control Algorithm Descriptions

A total of 13 controls were developed and tested for humidity, energy and IAQ performance. In all cases, ventilation rates were controlled using a real-time calculation of relative exposure and relative dose. Targets or limits were set depending on the control condition (i.e., month of year, indoor-outdoor humidity difference, etc.), and the ventilation fan was operated to meet those targets. The key characteristics summarized in Table 1 are schedule, sensors, relative dose target and cooling tie-in. Full details for all control strategies are documented in Less et al. (2016).

Schedule. Control strategies are considered scheduled if the controls function based solely on the month of the year, or on the hour of the day, with no sensor inputs. Scheduled controls included Controls 6, 8 and 12. These approaches generally relied on the consistent and predictable changes in outdoor humidity that occur over the course of the year. We used the monthly average differences in indoor and outdoor humidity from baseline simulations to determine the months targeted for over- or under-ventilation, and ventilation rates during these pre-determined months controlled using either a high or low relative dose target.

Sensors. Sensor-based strategies used either an outdoor humidity sensor, or two sensors – one indoor and one outdoors. All homes had a single HVAC system. Control 10 used a simple outdoor humidity cutoff. Control 13 used the annual outdoor median humidity ratio for each climate zone, and the controller over-vented when the real-time value was below the annual outdoor median, and it under-vented when above the real-time annual median. Control 14 provided a similar but more complicated example, where the 25th and 75th percentile outdoor humidity ratios were calculated for each month of the year, and these were used in real-time to either over- or under-ventilate. Two sensor strategies, Controls 2, 3, 4, 5, 7 and 9, varied in terms of their relative dose targets and cooling tie-in features. Two types of two sensor approaches were tried, one with a simple on/off indoor-outdoor humidity balance (called "Fixed sensor" in the Control Name column of Table 1), and the other with a proportional control approach ("Proportional sensor" in Table 1). In "Proportional sensor" control cases, the amount of over- or under-ventilation was proportional to the real-time difference between indoor and outdoor humidity ratios. This was done so that when humidity differences were large, large changes in ventilation rate were allowed, and when humidity differences were small, ventilation rates were adjusted only minimally. This was an attempt to avoid excessive over- or under-ventilation when there was little anticipated value from a moisture control perspective. "Fixed sensor" controls over-

or under-ventilated to their maximum allowed levels whenever the humidity balance shifted between indoor and outdoor.

Relative Dose Targets. While all controllers calculated relative exposure and relative dose in real-time, the targets used varied substantially, and were either fixed or variable. When using fixed relative dose targets, a threshold value of one was always used. Variable dose target controls set the dose target to either above or below one, depending on the control conditions. This leads to sometimes extended, continuous periods of either over- or under-ventilation (still with the exposure limit of 2.5). For example, in Control 6 the relative dose target took one of two values, depending on whether the indoor-outdoor moisture difference was expected to be positive or negative for that month (this expectation was determined from baseline simulations). So, for months-on-end the ventilation rate was either below or above the ASHRAE 62.2-2013 target rate, such that annual relative dose was less than one. A similar high or low dose target approach was used with the one-sensor Control 13 based on the annual median outdoor humidity ratio. The dose target was 0.5 during dry periods and 1.5 during humid outdoor periods (roughly equal to doubling ventilation rate and reducing by 33%). A more dynamic approach was used in the two-sensor, variable dose controls (Controls 2, 3, 4, 5, 7 and 9). Again, two relative dose targets were determined and the controller targeted one or the other depending on the direction of the indoor-outdoor moisture difference.

Cooling system tie-in. This approach was used as an isolated control strategy, as well as in combination with most of the other controls. The ventilation system was controlled to operate at full capacity during space cooling operation, sometimes subject to other constraints (e.g., only vent during cooling operation if indoor RH >55%). This approach was useful for two reasons. First, introducing high humidity outside air into this airstream before mixing with house air results in higher humidity ratio air passing over the cooling coil. This leads to more moisture removal for a given sensible load. Second, the sensible cooling load is increased through introduction of more outside air, and this increases cooling system runtime. The relative dose and exposure are reduced during this period of over-ventilation (at ~300% of 62.2 rate), such that the system does not ventilate for substantial remaining portions of the day.

SIMULATIONS

The REGCAP simulation tool was used to provide estimates of indoor humidity, energy use, air exchange rates, and relative dose and exposure for each control strategy. The model has recently been used in development of other smart ventilation controls that provide annual equivalence to 62.2, while varying ventilation rates with occupancy, time-of-day, outside temperature, and operation of other exhaust devices in the home (Turner and Walker 2012; Walker, Sherman, and Dickerhoff 2012; Less, Walker, and Tang 2014). The REGCAP simulation combines detailed models for mass-balance ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. Two zones are simulated: the main house and the attic (the separate attic is important if the HVAC system is located in the attic). REGCAP was implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance. TMY3 weather data were linearly interpolated from one-hour to one-minute time steps for use in the REGCAP. The decision to turn the whole house fan on or off using the smart ventilation controls was made once every ten minutes.

All simulations were of a high performance, single-family home that meets the U.S. DOE Zero Net-Energy Ready home requirements (U.S. Department of Energy 2013). The whole house ventilation systems were central fan integrated supply (CFIS) ventilations systems sized to 300% of the airflow requirement of ASRHAE 62.2-2013 (including infiltration credit; required airflow rates differed by house sizes and occupancy rates). The CFIS operated 20 minutes of every hour irrespective of heating or cooling demand. Other local exhausts were scheduled on a semi-random basis. House sizes of 100, 200 and 300 m² (referred to as small, medium and large) were studied together with moisture generation rates of 3, 6.5 and 11.8 kg/day (referred to as low, medium and high), respectively. These moisture generate rates were associated with two, four and six occupants, respectively. Occupancy was assumed to be continuous. More details of house characteristics can be found in Less et al. (2016). Fixed cooling and heating set

points of 24.4°C and 21.7°C were used, which match assumptions of the Building America reference home (Engebrecht and Hendron 2010). Simulations were first performed for baseline cases. These baseline simulations provide the comparison cases for all of the smart control cases. All 13 control strategies were tested for small homes with high moisture gains, medium sized homes with medium gains, and large homes with low gains.

Table 1 Comparison of key elements of 13 smart ventilation control strategies. Bold entries were identified as best performers and were tested in other home configurations.

ID	Control Name	Schedule	Sensors	Rel Dose Target	Cooling Tie -In
1	Cooling system tie-in	N	0	Fixed	Y
6	**Monthly seasonal**	**Y**	**0**	**Variable**	**N**
8	Monthly seasonal + Hourly	Y	0	Variable	N
12	Monthly seasonal + Cooling system tie-in	Y	0	Variable	Y
10	Fixed outdoor HR cutoff	N	1	Fixed	N
13	**Annual medians**	**N**	**1**	**Variable**	**N**
14	**Monthly quartiles**	**N**	**1**	**Variable**	**N**
2	**Fixed sensor**	**N**	**2**	**Fixed**	**N**
3	**Fixed sensor + Cooling system tie-in**	**N**	**2**	**Fixed**	**Y**
4	Proportional sensor	N	2	Fixed	N
5	Proportional sensor + Cooling system tie-in	N	2	Fixed	Y
9	**Fixed sensor + Variable dose target**	**N**	**2**	**Variable**	**N**
7	**Fixed sensor + Cooling system tie-in + Variable dose target**	**N**	**2**	**Variable**	**Y**

RESULTS

Baseline Simulations

For all baseline cases with non-smart ventilation, we evaluated the distribution of indoor relative humidity, the fractions of the year exceeding 60% and 70% RH, and the longest continuous periods exceeding these thresholds. The results are summarized for each climate zone in

Table 2. The variation in high humidity by house size and moisture gains is pictured in Figure 1. A summary of energy, IAQ and humidity performance is provided for all baseline cases in Less et al. (2016). Key conclusions from this baseline simulation analysis include the following:

- Annual hours of elevated indoor humidity above 60% RH were highly variable and were strong functions of the house size and moisture generation rates (see Figure 1), with smaller homes and higher moisture generation rates leading to higher indoor humidity. Fully 69% of all baseline simulations had less than 5% of annual hours above 60% RH, and 95% of cases had less than 5% of annual hours exceeding 70% RH. We consider indoor humidity to be of little concern in these cases, and subsequent analysis focuses on the high humidity cases.
- Maximum duration periods above 60% RH varied between one and eight days, by climate zone.
- Some locations had high indoor humidity all year (e.g., Miami and Orlando), whereas others experienced it only during summer months (e.g., Memphis and Baltimore).
- Shoulder seasons had the highest humidity, due to low sensible cooling loads and similar indoor and outdoor absolute humidity.
- Few high humidity hours occurred during either heating or cooling system operation (<10%).

Table 2 Annual humidity summary for cases with fan sized to 100% of 62.2-2013, averaged across house size and moisture generation rate

	Indoor Relative Humidity (%)						Annual Fraction		Maximum Duration (days)	
Climate Zone	Min	25th	Median	Mean	75th	Max	>60% RH	>70% RH	>60% RH	>70% RH
Miami	35	48	51	51	55	87	10%	1%	1.2	0.5
Orlando	31	45	49	49	53	77	8%	1%	2.5	0.6
Houston	26	44	49	49	54	77	9%	1%	2.0	0.3
Charleston	24	44	49	48	54	71	8%	0%	1.7	0.2
Memphis	20	36	44	42	49	63	2%	0%	0.2	0.0
Baltimore	17	28	40	38	46	62	1%	0%	0.2	0.0

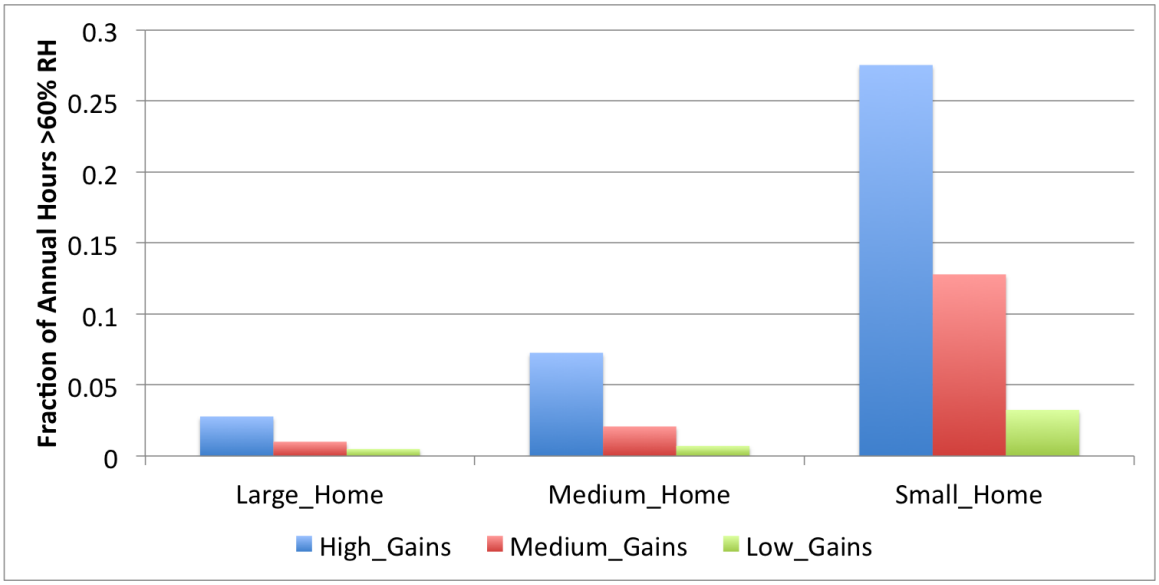

Figure 1 Summary of annual hours >60% RH as they vary with home size and indoor moisture gains, averaged across climate zones.

Smart Ventilation Control

Figure 2 shows reductions in annual hours >60% RH averaged across the six climate zones for each of the 13 control strategies. To focus on cases with the highest humidity, these values include only the small homes with high moisture gains. Key conclusions from analysis of these smart control simulations include the following:

- All smart controls increased HVAC energy use, but they also decreased hours of high humidity and shifted overall indoor humidity distributions downward (see Figure 3). Energy use was strongly dependent on the heating demand of the climate zone and the ventilation strategy during heating periods (over-ventilation during winter led to large energy use increases in some cases). In general, smart controls used the least energy and were the most effective in the hottest climates with the highest indoor humidity.
- When averaged across climate zones, the best performing strategy (Control 7, two sensor, variable dose target with cooling tie-in) was able to shift roughly 10% of annual hours from above to below the humidity thresholds, with energy consumption that varied significantly by climate zone (see black triangles in Figure 4).

This energy use was largely driven by the heating demand in a given location. In the most humid location (Miami), Control 7 reduced 16% of annual hours from above to below 60% while increasing energy use by only 277 kWh in the small home with high moisture gains.

- In cases of most concern (i.e., small homes with high moisture generation rates), there were still substantial numbers of hours of elevated indoor RH. As pictured in Figure 4, between 20 and 25% of annual hours remained >60% in the most humid locations. Mechanical dehumidification may still be required in these homes. Future work should investigate the interactions between smart controls and supplemental dehumidification systems.
- Sensor-based strategies outperformed schedule-based approaches. Though Control 12, which combined monthly relative dose targets with a cooling tie-in feature, was the third best in reducing high humidity hours in small homes with high moisture gains (see Figure 2).
- Two sensors were generally better than one, as they were able to respond to real-time changes in indoor and outdoor humidity. The one-sensor Control 13 based on annual median outdoor humidity ratios was reasonably effective, though less so than the no-sensor Control 12. Given the desirability of using web-based weather data for smart ventilation control, future work should investigate ways to improve these outdoor-only sensor approaches.
- The cooling tie-in feature had varied results, but it generally led to better performance with a small energy penalty (roughly 450 kWh in small homes and 580 kWh in medium homes), and we recommend this approach in combination with schedule- or sensor-based controls.
- Controls using variable dose targets were more effective, but fixed dose approaches worked well in locations with substantial heating demand.

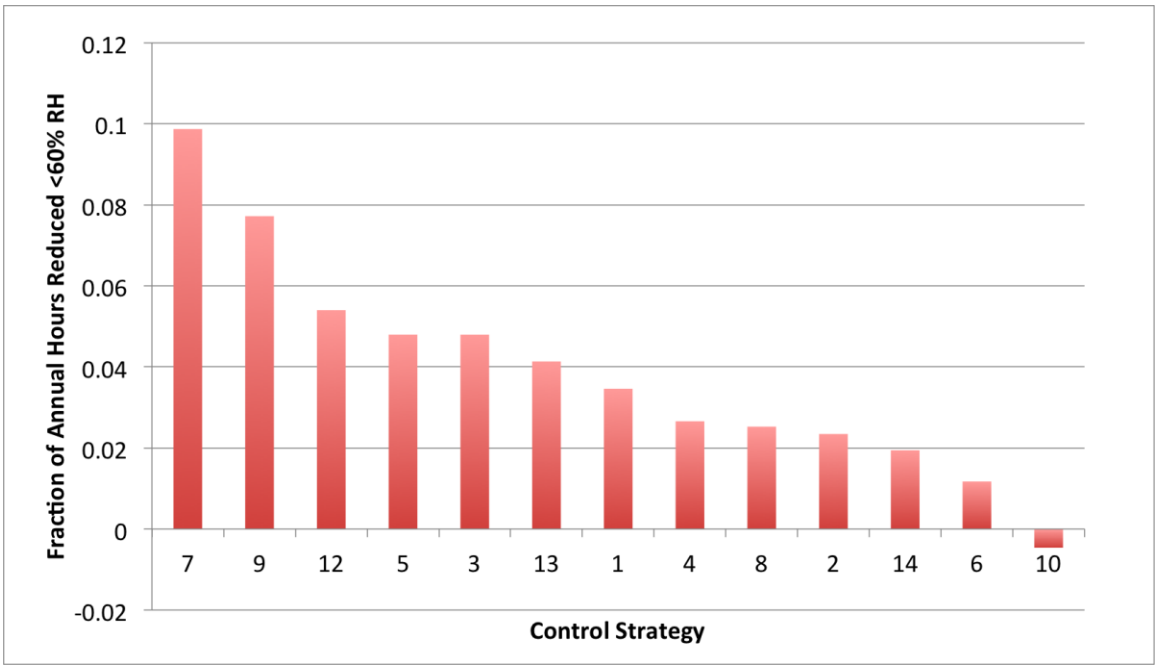

Figure 2 Reductions in high humidity hours for the 13 strategies in small homes with high moisture gains, averaged across all climate zones. Reductions are expressed as fractions of the year, such that a value of 0.10 means that 0.10 * 8,760 = 876 hours were reduced from above to below 60% RH.

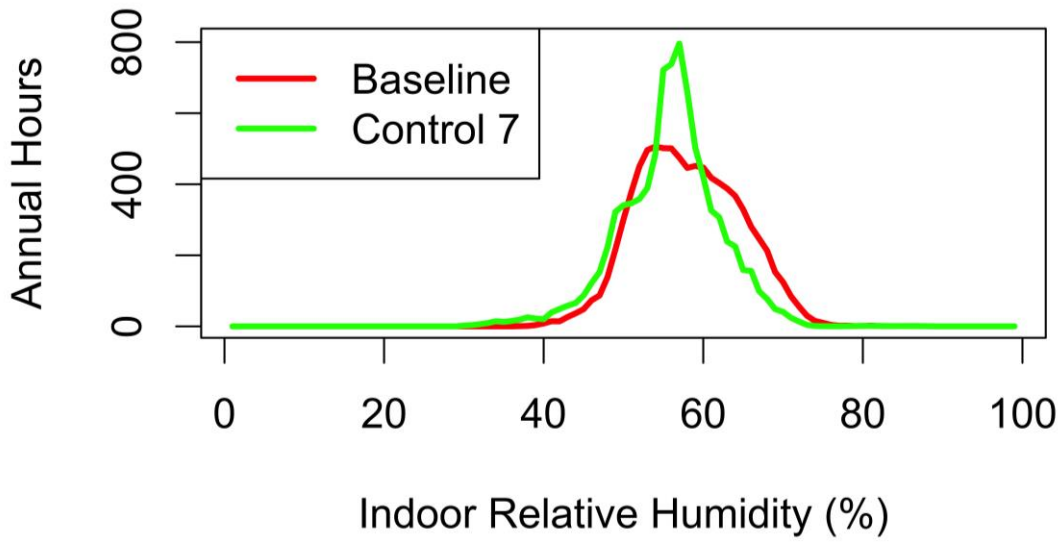

Figure 3 Histograms showing annual distributions of indoor RH in baseline and Control 7 cases, for a small home with high moisture gains in Miami, FL.

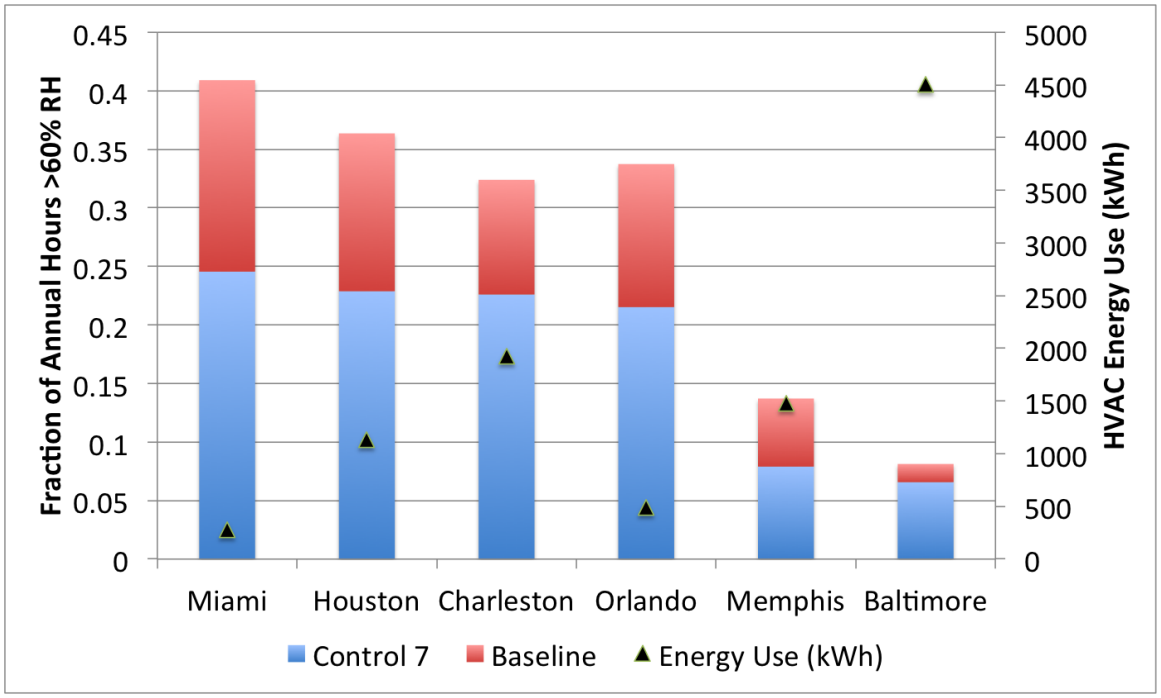

Figure 4 Fraction of the year >60% RH in Baseline (red) vs. Control 7 (blue) cases, and changes in annual HVAC energy consumption from baseline when using Control 7 (black triangles, 2nd y-axis). Includes only small homes with high moisture gains.

SUMMARY AND CONCLUSIONS

- High indoor humidity was not an issue in many combinations of location, house size and moisture gains. The most problematic cases were small homes with high moisture gains, where between 5 and 40% of annual hours were >60% RH.
- Smart ventilation controls were effective at reducing indoor humidity levels, and they maintained air quality equivalent to or better than a continuous fan sized to 62.2-2013. The best performing strategy was Control 7 that used both indoor and outdoor sensors and a cooling system tie-in. It was able to reduce 16% of annual hours <60% RH in a small Miami home using under 300 kWh.
- Estimated energy use for smart controls was in the same range as that used by mechanical supplemental dehumidification strategies.
- In the most challenging cases, indoor humidity remained >60% for 20 to 25% of annual hours despite use of smart controls, and use of supplemental dehumidification in humid climates may be necessary to achieve acceptable levels in these high performance homes. Our next steps are to evaluate how smart ventilation controls interact with and compare to a supplemental mechanical dehumidification strategy.

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