Development of a Seasonal Smart Ventilation Controller to Reduce Indoor Humidity in Hot-Humid Climate Homes

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ABSTRACT

Controlling indoor humidity is important in homes, because high indoor humidity is associated with occupant health and building durability issues. Ventilation is often used to avoid peaks of moisture in homes, such as in kitchens and bathrooms. However, in hot-humid climates, outdoor air can have higher humidity than indoors, and continuous whole house ventilation can lead to increases in indoor humidity levels. This problem is exacerbated in high performance homes, because their efficient building envelopes limit the operation of the cooling system, which also provides incidental dehumidification. This paper analyzes a time-shifting approach to smart ventilation control that takes advantage of changes in outdoor and indoor humidity, essentially venting more when dryer outside and less when more humid outside. The changes in whole house airflow are controlled in such a way that exposure to air pollutants is equivalent to a continuously operating, fixed airflow system. Specifically, this paper presents the development and initial testing of a seasonal smart ventilation controller, based simply on the month of the year and the net-humidity balance for the month between inside and outside. We assessed high performance test homes with varying floor areas and moisture generation rates across a variety of hot- and mixed-humid climates in the south-eastern U.S., using ventilation simulation software specially adapted for this analysis. We present the results from baseline simulations, with continuous fans sized at 0%, 50% and 100% of the ASHRAE 62.2-2013 fan flow rates. From this analysis, we develop a seasonal control strategy. Finally, we present preliminary results from use of the proposed seasonal controller. The results include comparisons of IAQ, energy use and indoor humidity levels.

KEYWORDS

Humidity, ventilation, IAQ, homes, hot-humid climates, high performance homes, smart ventilation, controls

1 INTRODUCTION

Elevated indoor humidity levels in homes represent a risk to occupant thermal comfort and health, as well as building durability. Indoor relative humidity is commonly controlled between 40% and 60% for comfort, health and building durability reasons. In most homes, the indoor humidity is kept within this range by high levels of natural air exchange and by operation of the central cooling system and its associated moisture removal. High performance homes are more efficient from the thermal point of view, and their cooling system operates less, which reduces the associated moisture removal. Ventilation is often cited as a secondary contributor to high indoor relative humidity in high performance homes in hot humid climates, and questions have been asked about lowering mechanical ventilation rates. Several studies have assessed the costs and effectiveness of strategies to reduce indoor humidity levels in high performance, humid climate homes (Kerrigan & Norton, 2014; Moyer, Chasar, Hoak, & Chandra, 2004; Rudd, 2013b; Rudd & Henderson, Jr., 2007; Rudd et al., 2005). The main goal of these efforts was to reduce the number of hours above 60% RH to an unspecified, "acceptable" level. Strategies have included dehumifiers, energy recovery ventilators (ERV) and enhanced cooling system control strategies.

This paper investigates the use of smart ventilation controls to reduce the impact of ventilation on indoor moisture in high performance, low sensible load homes in humid climates. Our smart ventilation controller is designed to reduce the number of hours of high indoor humidity, without worsening occupant exposure to indoor pollutants. To do this, we introduce the concept of *relative exposure,* used to quantify indoor air quality (IAQ) (Sherman, Mortensen, & Walker, 2011; Sherman, Walker, & Logue, 2012). Relative exposure is represented as a fractional value, comparing the pollutant concentration in the control case against a base case continuously vented to the ASHRAE 62.2-2013 Total Ventilation Rate (ANSI/ASHRAE, 2013). If the annual average relative exposure is equal to one, the occupants have received the equivalent exposure to indoor contaminants. An annual average relative exposure below one means exposure is lower than the standard, and values greater than one indicate exposure is higher than the standard. Our smart controller uses this concept to ensure equivalent annual exposure while time-shifting ventilation to periods that are advantageous from a humidity perspective.

2 APPROACH

To assess the humidity impacts of mechanical ventilation and of smart controls, we used the REGCAP simulation software to simulate high performance homes in hot humid U.S. climates. REGCAP is a physics-based model with mass, moisture and heat balance modules, simulated on a one-minute time-step in C++. The REGCAP model is described in detail in Appendix 1 of (Walker & Sherman, 2006). The REGCAP model was first used to run baseline simulations, with continuous fans sized to ASHRAE 62.2-2013. Analysis of these baseline simulations led to the development and testing of the seasonal smart control strategy.

2.1 Test house and parameters of interest

In our simulations, we varied the climate zones, home size, fan size, internal moisture generation rates and sensible heat gains for a total of 162 combinations (see Table 1). A variety of locations were chosen in hot- and mixed-humid climate zones to assess the effectiveness of humidity control by smart ventilation control. These locations were chosen because past simulations have shown them to have high indoor humidity (Martin, 2014), or they were the representative cities in humid U.S. climate zones 1A-4A. Three one-story house geometries were chosen with varying conditioned floor areas (Small-Size: $100m^2$, Medium-Size: $200m^2$, Large-Size: $300m^2$). The building envelopes and equipment performance specifications are based on the requirements[1] of the U.S. DOE Zero Energy Ready home (U.S. Department of Energy, 2013). All test cases are representative of very high performance, efficient homes, with airtight envelopes (2.5-3 ACH_{50}), insulation levels compliant with the International Energy Conservation Code 2012, efficient windows, HVAC ducts located in conditioned space, etc.

Three moisture generation rates were used to represent low, medium and high occupancy homes, with 3, 6.5, 11.8 kg/day, respectively. Sensible internal heat gains also varied with occupancy and were calculated using the formula for the reference home in the Home Energy Rating System (HERS) Standards (RESNET, 2006) Table 303.4.1(3). Values ranged from

[1] DOE Zero Energy Ready Home air-tightness requirements: Climate-Zones1-2:ACH_{50}=3, Climate-Zones3-4:ACH_{50}=2.5.

180 to 928 watts. We assumed that the moisture and sensible loads are generated evenly throughout the day.

The whole house ventilation fan was sized to meet ASHRAE 62.2-2013 requirements, which varies fan flow with floor area and occupancy. An infiltration credit was deducted from the total required airflow, depending on the airtightness and climate zone using the infiltration credit calculations in the standard. One type of common mechanical ventilation system was simulated, the central fan integrated supply (CFIS). CFIS is a duct from outside to the return of the central air handler, and when the central fan operates, outside air is introduced. The CFIS system has the potential to provide the most efficient humidity removal, because the air flowing over the cooling coil including the air from outside can be at a higher humidity than if the outdoor air first mixed with indoor air and then entered the cooling system. We took into account three fan sizes: the value 0 to indicate no continuous ventilation, 0.5 to represent the 50% of the rate required by ASHRAE 62.2-2013 and the value 1 to accomplish the 100% of the required rate. Local exhausts simulated in REGCAP included bathroom and kitchen fans, as well as vented clothes dryer.

Table 1: Synthesis of all the parameters for the simulations.

<table>
<tr><td rowspan="6">CLIMATE ZONES</td><td colspan="2">Miami, FL (1A)</td><td colspan="2">72 HDD</td></tr>
<tr><td colspan="2">Orlando, FL (2A)</td><td colspan="2">302 HDD</td></tr>
<tr><td colspan="2">Houston, TX (2A)</td><td colspan="2">311 HDD</td></tr>
<tr><td colspan="2">Charleston, SC (3A)</td><td colspan="2">1049 HDD</td></tr>
<tr><td colspan="2">Memphis, TN (3A)</td><td colspan="2">1631 HDD</td></tr>
<tr><td colspan="2">Baltimore, MD (4A)</td><td colspan="2">2537 HDD</td></tr>
<tr><td>HOME SIZE</td><td>LARGE (300sqm)</td><td colspan="2">MEDIUM (200sqm)</td><td>SMALL (100sqm)</td></tr>
<tr><td>FAN SIZE</td><td>0</td><td colspan="2">0.5</td><td>1</td></tr>
<tr><td>MOISTURE GENERATION RATES</td><td>HIGH (11.8 kg/day)</td><td colspan="2">MEDIUM (6.5 kg/day)</td><td>LOW (3 kg/day)</td></tr>
<tr><td>VENTILATION TYPE</td><td colspan="4">CFIS</td></tr>
</table>

2.2 Outdoor Humidity

In order to understand the potential for smart ventilation strategies to mitigate moisture issues in high performance homes, it is first essential to understand patterns in outdoor humidity, as represented in Typical Meteorological Year (TMY3) weather data files. We assessed these patterns by performing seasonal decomposition on the outdoor humidity data, breaking the variability down into three components: the monthly, the daily and the hourly trends. As pictured in Figure 1, the variability in outdoor humidity values decreases going from monthly, to daily and hourly periods. The monthly variation in outdoor humidity is fairly predictable across locations, with higher values of outdoor humidity during summer months and lower values during the rest of the year. Daily patterns are not predictable, because they are not driven by diurnal or annual seasonal patterns. Control strategies that take advantage of daily humidity variability would have to be sensor-based. Hourly patterns are diurnally driven and therefore more predictable, but variation within hours of a day is small, so the value of hourly control is limited. From these considerations, control based on the month of the year is both possible and will have the most benefit in controlling indoor humidity.

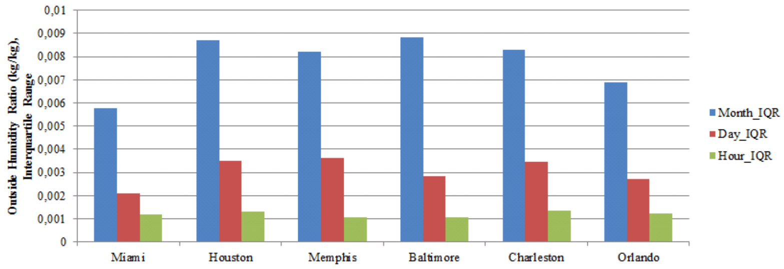

Figure 1: Interquartile ranges of outdoor humidity in select hot-humid cities based on monthly, daily and hourly decomposed trends.

2.3 Initial Simulations to investigate impact of ASHRAE 62.2 ventilation on indoor humidity – Baseline Simulations

2.3.1 Indoor Humidity

For all baseline cases, we evaluated the average indoor relative humidity and the proportion of the year with indoor relative humidity above 60% and 70%, as this is the primary metric used in the literature to assess humidity problems and interventions. Table 2 shows summary statistics for each location aggregated across varying floor areas and occupancy rates. All locations had substantial periods of the year above 60% and 70% RH in all locations. The indoor humidity generally worsens as climates become both hotter and more humid.

Table 2: Proportion of the year with indoor relative humidity above 60% and 70%, values averaged across all parameters (house size, occupancy rate, flow rates)

Climate Zone	**Median fraction of the year (%)**		**Annual Average of Median values of RH (%)**
	>60%	**>70%**	
Miami	87	41	67
Orlando	70	28	65
Houston	64	34	64
Charleston	64	32	66
Memphis	38	13	57
Baltimore	31	14	52

Given that indoor humidity issues vary by climate zone, smart ventilation control strategies may also need to differ based on location. Indeed cities such as Miami and Orlando present yearlong humidity problems, with periods of high humidity spread throughout the year. The highest indoor humidity periods tend to occur in “shoulder seasons”, when outdoor humidity is increasing towards its summer peak, but sensible loads are not yet driving cooling system operation and dehumidification. Such shoulder season humidity peaks are evident in the month of February in Figure 2, which shows the annual pattern of indoor humidity in Orlando. Also evident in Figure 2 is that indoor humidity is above 60% RH nearly all months of the year. Conversely, for Baltimore (see Figure 3), issues occur only during the summer period.

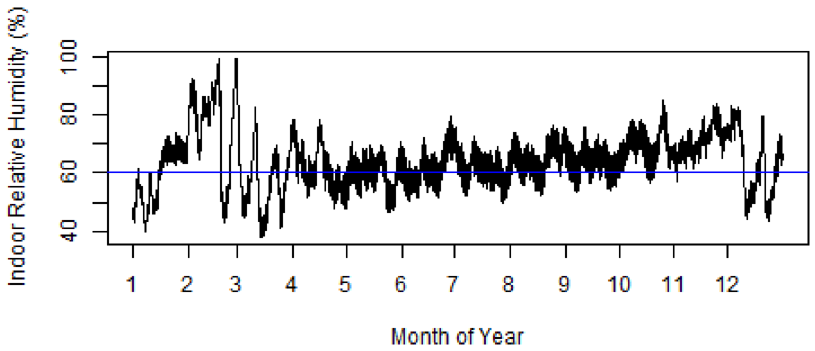

Figure 2: Indoor Humidity trend in Orlando.

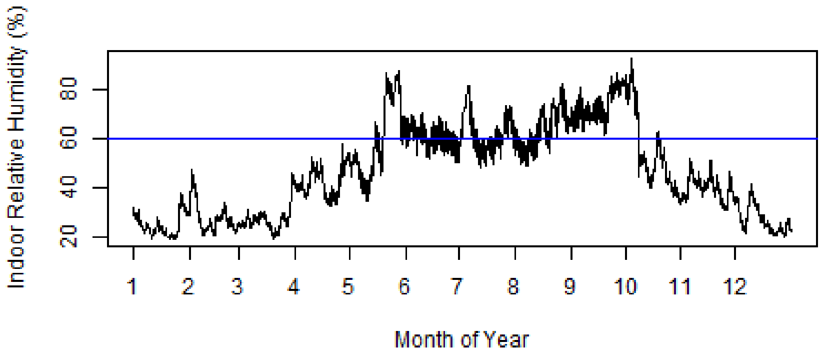

Figure 3: Indoor Humidity trend in Baltimore.

2.3.2 Net-moisture balance and effects of house parameters

From first principles, the simple mass balance for moisture suggests that ventilation will either transport water vapour into or out of the home, depending on the sign of the humidity ratio difference ($w_{house} - w_{outside}$). Positive values lead to moisture removal from the house and negative values lead to moisture transport into the house.

$$\dot{m}_{water} = \dot{m}_{air} \times (w_{house} - w_{outside}) \tag{1}$$

m_{water} = mass flow of moisture, *kg*
m_{air} = mass flow of air, *kg*
w_{house} = humidity ratio of house, *kg/kg*
$w_{outside}$ = humidity ratio outside, *kg/kg*

For each simulated test case, we calculated the humidity ratio difference (HRdiff) between the house and outside for every hour of the year. This HRdiff is shown for an example case in Figure 4. We then averaged these values over different time periods of interest, namely annually and monthly. We refer to this annual average as the net-humidity balance. For each combination of house size, occupancy rate and climate zone, there is an annual net-humidity balance (average of all HRdiff values for the year), which is either positive or negative. Positive means that on average for the year, it is more humid inside than outside, and more ventilation will provide net-moisture removal. Negative means that on average, it is more humid outside than inside, and more ventilation will provide net-humidification. These same principles function on a monthly basis as well, which we explore below in section 2.3.3 in development of our seasonal control algorithm.

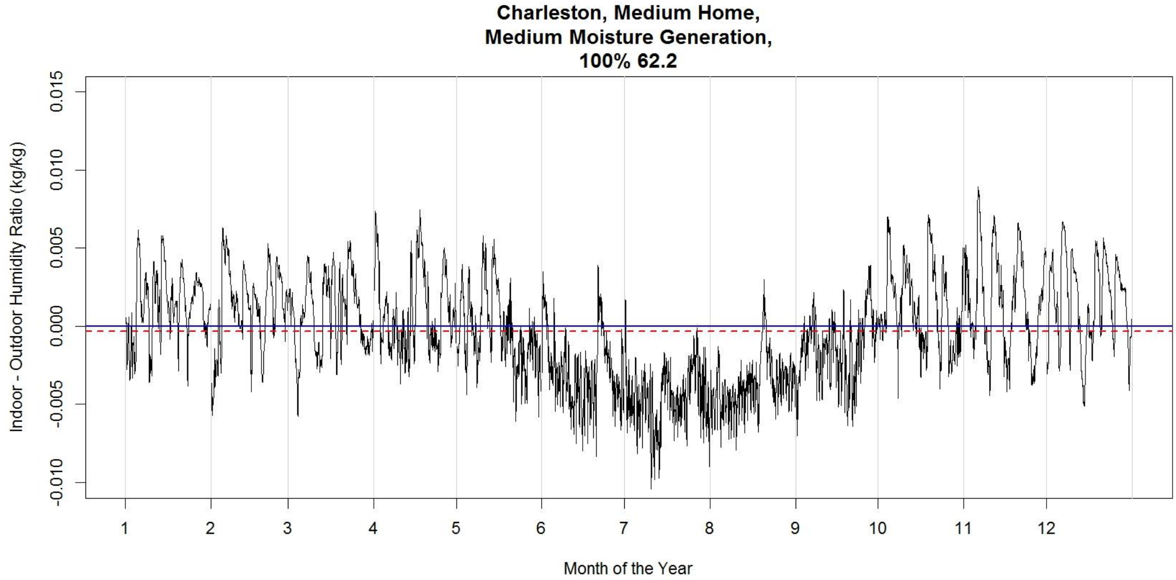

Figure 4: Time series plot of hourly humidity ratio differences (HRdiff) for a medium size Charleston home with medium moisture generation rate, and ventilation sized at 100% of 62.2-2013. Solid blue line represents value of zero, and the dashed red line is the annual average for this case.

We expect that the value of ventilation over the course of the year will vary by climate zone, and that this will depend on the sign and magnitude of the net-humidity balance. It will also vary by home size and moisture generation rates. In order to understand these effects independently, we developed a linear multiple regression model to predict the net-annual humidity balance using three factor variables—climate zone, home size and occupant density (p-value = < 2.2e-16; Adjusted R^2 = 0.9811). The resulting coefficients are provided in Table 3, with a reference intercept value of -0.0017 kg/kg in a large Miami home with high occupant density.

Table 3: Coefficient estimates from multiple linear regression model of annual humidity ratio difference on climate zone, house size and occupant density.

Parameter	Coefficients	Parameter	Coefficients
Miami_HouseLarge_HighDensity	-0.00171	HouseSize_Med	0.000389
Houston	0.000999	HouseSize_Small	0.001225
Orlando	0.001026	OccDensity_Med	-0.00075
Charleston	0.001752	OccDensity_Low	-0.00142
Memphis	0.001947		
Baltimore	0.002667		

From these regression coefficients, it is clear that climate zone, home size and occupant density have substantial impacts on the net-annual humidity balance. Annual net-humidity balances become more positive as we progress from Miami through Baltimore, with positive model coefficients of increasing size as climates become progressively less humid. Similarly, for any given moisture generation rate and climate zone, the smaller sized home will have higher humidity than the larger size home. This is reflected in positive model coefficients for small and medium size homes that get larger as the home gets smaller (Medium = 0.000389 and Small = 0.00123). Similarly, for any home size and climate zone, a higher moisture generation rate (represented by occupant density in this model) will lead to higher levels of indoor humidity compared with a lower generation rate. This is reflected in negative model coefficients for medium and low occupant densities that get more negative as occupancy decreases (Medium = -0.00075 and Low = -0.00142). To illustrate, a large home in Charleston goes from a slightly positive humidity balance with high moisture generation (0.000039 kg/kg) to increasingly negative values when decreasing the moisture generation rate to medium (-0.00072 kg/kg) and low (-0.0014 kg/kg). From this, we can see generally that large homes with low occupancy will experience the most increase of indoor humidity when ventilating (largest negative values of net-humidity balance), and that small homes with high occupancy will experience the most decrease of indoor humidity when ventilating.

We tested fans sized at 0%, 50% and 100% of the 62.2-2013 ventilation rates to assess the impacts of changing the ventilation rate. The impact of smaller or larger fans depended on the net-humidity balance. As expected, with a positive net-humidity balance, ventilation dehumidified the space, and more ventilation dehumidified more. With a negative net-humidity balance, ventilation humidified the space, and more ventilation humidified more. We see this illustrated in Figure 5, particularly in the “high” and “low” moisture generation categories. The net-humidity balance is positive and large in the “high” cases (left figure), and increasing ventilation from 0% to 50% to 100% of 62.2 rates reduces periods of high indoor humidity from approximately 50% of the year down to 30% (right figure). In “low” cases, the net-humidity balance is negative (left figure), and increasing ventilation from 0% to 100% of 62.2 rates leads to increased periods of high humidity from approximately 10% to 20% of the year (right figure). These effects are non-linear, and they mostly indicate the direction, but not magnitude, of the changes in indoor humidity as ventilation rates are varied.

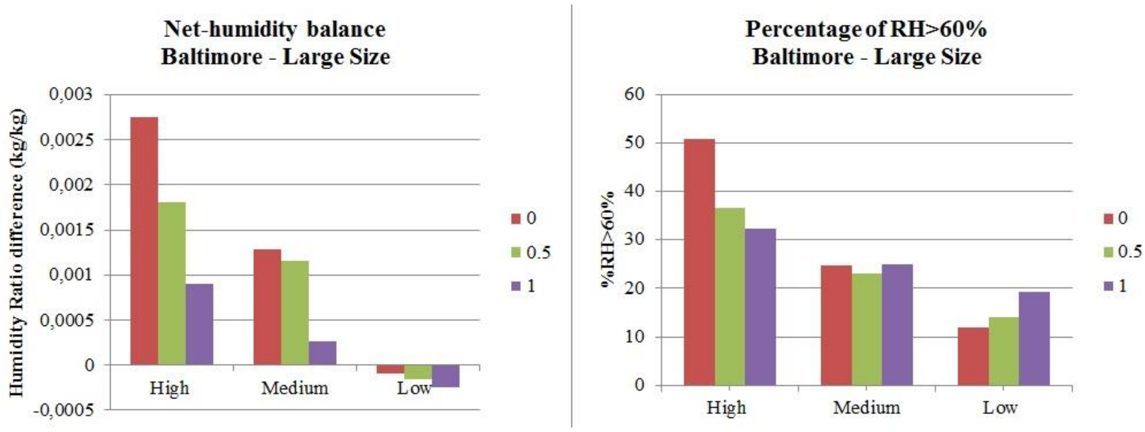

Figure 5: Relation between net-humidity balance and periods of high humidity in an example case of a large sized home in Baltimore with varying moisture generation rates and whole house ventilation rates (0, 50%, 100% 62.2)

2.3.3 Seasonal and monthly variation in simulated humidity problems

We have discussed how the effect of ventilation on indoor humidity depends on the annual net-humidity balance between inside and outside. This same effect occurs on a monthly basis. In Table 4, we present the monthly net-humidity balances for the 100%[2] of ASHRAE 62.2-2013 flow rates, averaging across home sizes and occupancy rates. As before, positive values (green cells) indicate the ventilation will provide a net-humidity benefit, and negative values (red cells) indicate a net-penalty. Light-green and pink cells indicate months with marginal smaller net-humidity differences. Each climate zone has a clear seasonal pattern, with negative values in the summer and positive values during the other months of the year.

[2] In this work we will show only the results for a fan sized at 100% of ASHRAE 62.2-2013.

Table 4: Monthly mean differences between indoor and outdoor humidity

1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Miami	0.0019	0.0014	0.0006	-0.0008	-0.0028	-0.0049	-0.0055	-0.0053	-0.0046	-0.0031	-0.0006	0.0011
Houston	0.0012	0.0012	0.0014	0.0009	-0.0012	-0.0044	-0.0057	-0.0057	-0.0030	0.0013	0.0019	0.0018
Memphis	0.0019	0.0014	0.0018	0.0012	0.0003	-0.0024	-0.0040	-0.0032	-0.0014	0.0021	0.0023	0.0020
Baltimore	0.0015	0.0017	0.0014	0.0016	0.0009	0.0001	-0.0018	-0.0010	0.0005	0.0027	0.0018	0.0017
Charleston	0.0018	0.0017	0.0012	0.0013	-0.0001	-0.0027	-0.0045	-0.0037	-0.0012	0.0017	0.0020	0.0020
Orlando	0.0012	0.0018	0.0011	0.0012	-0.0012	-0.0031	-0.0056	-0.0045	-0.0029	-0.0011	0.0015	0.0017

When comparing between the house size and occupancy rate parameters, the seasonal monthly patterns do not change in most cases, but the magnitude of the humidity differences shift up or down. In cases where the seasonal pattern does shift, the mean values of the humidity differences during those months tend to be small (i.e., an order of magnitude smaller than the differences found in non-shifting months). This limits the overall impact of any given month going from a positive to negative humidity difference. To account for this shifting on the margins, we design our seasonal control to be based on the dark red months.

This average seasonal pattern is not the best fit in all cases. For example, one of the worst-cases is a large, low-occupancy home in Miami when compared to the average in Table 4. In this case, two months are added to the dark red category, with fairly large negative humidity differences, and our control based on the average will over-ventilate during these months, leading to higher humidity. But in most cases, these shifts are smaller and less important.

2.4 Proposed seasonal control strategy

Based on the previous analysis, we present our proposed seasonal ventilation control strategy in Table 5. The red months are the periods when ventilation is a liability, and the green months when ventilation is a benefit. Therefore a seasonal controller should increase the ventilation rate during green months and decrease it during red months. The magnitude of these increases and decreases must be designed so that annual exposure to pollutants is equivalent with a continuous fan. For our control strategy, this means targeting different relative exposure values in different months (see Table 5). In red months, we target a fixed exposure of 1.5, which reflects a reduction of approximately 33% in the ventilation rate. There are differing numbers of red months depending on the climate zone. So, for each climate, we calculated the required exposure target for the green months, such that the annual average would be equal to one. A real-time ventilation (RTV) controller was then used to achieve these exposure targets. The RTV controller used the equivalence approach (Sherman, M. H., Walker, I. S., & Logue, J. M. (2012) to operate the CFIS system to achieve the target exposure rates.

Table 5: Values of the Exposure Targets set for different months of the year.

	Green Months	Exposure Target	Red Months	Exposure Target	Green Months	Exposure Target
Miami	Jan-Apr	0.46	May-Oct	1.5	Nov-Dec	0.46
Orlando	Jan-Apr	0.46	May-Oct	1.5	Nov-Dec	0.46
Houston	Jan-Apr	0.608	May-Sep	1.5	Oct-Dec	0.608
Charleston	Jan-May	0.72	June-Sep	1.5	Oct-Dec	0.72
Memphis	Jan-May	0.72	June-Sep	1.5	Oct-Dec	0.72
Baltimore	Jan-June	0.876	July-Aug	1.5	Sep-Dec	0.876

2.4.1 Preliminary results and discussion

We implemented this seasonal control strategy using the REGCAP simulation tool, and here we show preliminary results for the medium sized home with medium occupancy rate using a CFIS ventilation system (see Table 6). The proportion of the year over 60% and 70% humidity is presented, along with the maximum time periods continuously above 60% and 70% RH. These values are presented and compared for the baseline and control cases, and the changes are summarized for each, along with energy use for the control strategy.

Table 6: Performance summary of the seasonal smart control strategy.

	BASELINE					SEASONAL CONTROL					**COMPARISON**				
	R60 %	R70 %	Max R60 days	Max R70 days	Total KWh	R60 %	R70 %	Max R60 days	Max R70 days	Total KWh	R60 %	R70 %	Reduc% R60 days	Reduc% R70 days	Total KWh
Miami	88	41	26	10	3700	80	29	21	5	4007	**-9**	**-30**	**-16**	**-50**	**+338**
Orlando	68	26	25	23	5358	58	18	12	9	5737	**-14**	**-30**	**-67**	**-23**	**+379**
Houston	64	32	29	16	10649	57	27	23	12	10917	**-10**	**18**	**-21**	**-28**	**+267**
Charles.	64	31	0	47	10994	62	23	0	6	11337	**-4**	**-24**	**0**	**-47**	**+343**
Memph.	38	12	16	5	16172	33	10	14	5	16710	**-11**	**-21**	**-17**	**-4**	**+538**
Baltim.	30	14	45	0	22463	29	14	30	0	29691	**-3**	**-1**	**-34**	**0**	**+228**

The control strategy increased HVAC energy use in all cases. The controller was most effective in the most humid climates, but was not effective in Baltimore. In general, the controller was more effective at reducing hours above 70% than those above 60%. These higher humidity hours are the most important to eliminate, so the strategy was having some success. Nevertheless, our maximum impact is only a 30% reduction in annual hours above 70% RH, which leaves substantial periods of high humidity despite smart control. However, the controller substantially reduced the longest continuous time periods of high humidity. These sustained periods of continuously high humidity may be the most important to interrupt and shorten, and the controller succeeded at doing this.

3 CONCLUSIONS

The smart seasonal control of ventilation rates leads to improved indoor humidity control in the more humid climates, with modest increases in annual energy use. It is less effective in intermediate climates. Given that the maximum reduction in high humidity hours was around 30% in Miami and Orlando, other smart control strategies are worth developing. We are in the process of testing more advanced seasonal control strategies, as well as real-time strategies using indoor and outdoor humidity sensors. Yet, ventilation is a secondary factor affecting indoor humidity, and smart ventilation controls are unlikely to be a fully sufficient solution on their own. They may need to be implemented alongside mechanical dehumidifiers or other solutions, which we are also exploring in future work.

4 ACKNOWLEDGEMENTS

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