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Energy Savings and Comfort Enhancement Potential of a Smart Residential Ventilation Control Strategy

FSEC-PF-475-18-R01

January 25, 2022

Presented at

2018 ACEEE Summer Study on Energy Efficiency in Buildings

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ABSTRACT

Mechanical ventilation is vital in modern homes to ensure adequate indoor air quality. However, builders, contractors, and homeowners may perceive best practice as a risk, for example if invoked when outdoor conditions may compromise comfort and energy use. ASHRAE Standard 62.2-2016 defines best practice, yet code specifications vary nationally. Although enthalpy recovery is advocated in efficient home design to reduce risk, additional risk management is available from taking advantage of the natural daily and seasonal temperature and humidity cycles.

We describe a smart ventilation system using outdoor temperature and moisture-based control. The main principle is to shift ventilation from time periods that have large indoor-to-outdoor temperature and moisture differences to periods when these differences are smaller and their energy and comfort impacts are expected to be less. Fan flow rates are reduced when outdoor temperature and moisture levels deviate far from desired indoor conditions, and are increased at other times to ensure overall air exchange, and chronic and acute exposure to pollutants, is maintained. Online weather and smart thermostat data can be used as control inputs, so no specific measurement devices are needed. This makes for a very low cost/high reliability solution.

Using the smart ventilation scheme demonstrated 10% average monthly cooling energy savings in two full-scale identical side by side test homes in Florida. The change in sensible ventilation load was much higher at 73%. Parametric simulations show similar savings for heating and cooling across North America climates demonstrating smart ventilation as a robust efficiency measure.

Introduction

Whole-house mechanical ventilation is a critical component to a comprehensive strategy for good indoor air quality (IAQ) in tight homes. However, due to lack of integration with standard heating and cooling systems, and perceptions about risks related to increased energy use, increased cost, and decreased comfort, voluntary and code-required adoption varies amongst regions (Martin 2014). Smart ventilation controls (SVC) manage risk by optimizing mechanical ventilation operation to reduce the heating and/or cooling loads, improve management of indoor moisture, and maintain IAQ equivalence according to ASHRAE Standard 62.2 (Sherman, Walker, and Logue 2012). During periods that provide energy, comfort, and/or IAQ advantages, SVC systems ventilate more, and they operate less during periods that provide a disadvantage.

Previous studies by Lawrence Berkeley National Laboratory (LBNL) have simulated smart ventilation strategies that included the effects of other fans operating in the home as well as passive ventilation systems (Sherman and Walker 2011). These studies included development of a ventilation model to include control algorithms and IAQ calculations for evaluating performance of variable ventilation rate systems. LBNL used these simulations to develop a smart ventilation algorithm based on a temperature threshold (Less, Walker, and Tang 2014). Recently, LBNL simulation techniques have been used to investigate the effect of smart ventilation control on indoor relative humidity (RH) (Less and Walker 2016). No prior published research on lab or field testing of smart ventilation control systems is available; however, developing "smarter" ventilation systems will enable the residential sector to more reliably design, install, and operate mechanical ventilation systems to achieve best-practice IAQ.

LBNL work on ventilation equivalence for intermittent ventilation systems was adopted by ASHRAE Standard 62.2-2016 (62.2- 2016) in the form of Appendix C. This provides a procedure to calculate pollutant exposure resulting from varying ventilation rates, relative to a continuous rate, and termed "relative exposure" (RE). Averaged exposure over a chosen time period achieving a value of 1.0 dictates that exposure to pollutants is equivalent to a continuously operating mechanical ventilation system. At no time can a time varying ventilation system produce an RE that exceeds five times the baseline.

This report describes an algorithm for SVC that varies mechanical ventilation airflow through interpretation of current and historical outdoor temperature and absolute humidity (W). The algorithm, developed by the Florida Solar Energy Center (FSEC), optimizes delivery of mechanical ventilation airflow on a daily cycle to minimize sensible and latent load impacts. While the algorithm could be used to control a ventilation system with heat or enthalpy recovery, this work focuses exclusively on the impacts of ventilation flow modulation. Flow modulation via SVC has the potential to achieve similar ventilation load reductions at a reduced cost due to the ability to utilize inexpensive components (Lubliner 2016). Simulations were conducted to tune the algorithm with differing seasonal adjustment factors to 1) maximize heating and cooling energy savings compared to continuous ventilation, 2) maintain similar indoor RH, and 3) achieve RE with respect to 62.2-2016. Experimental testing of the algorithm was conducted in central Florida, and utilized sensor-based measurements of weather parameters. However, commercialized systems could leverage online weather data available from internet-connected devices such as smart thermostats.

Algorithm Description

In all locations, optimizing ventilation according to outdoor temperature is desirable. However, in central Florida as well as other humid locations, outdoor moisture levels are a legitimate concern for ventilation since outdoor dew points are frequently above 70°F. To account for these factors, the algorithm examines the preceding 24-hour period and compares the recursively weighted hours with the current hour and seeks to minimize the sum of the square deviations from multiple targets: difference between indoor and outdoor temperature and difference between indoor and outdoor W. If desired, a weighting can be assigned to each parameter (X) to increase the sensitivity of the algorithm towards a parameter.

$$RSS = \sqrt{(\Delta T * X_T)^2 + (\Delta W * X_W)^2}$$

where
ΔT (°F) = (indoor temperature) – (outdoor temperature)
X_T = delta temperature weight
ΔW (g/m^3) = (indoor moisture) – (outdoor moisture)
X_W = delta moisture weight

The time weighted RSS (Average (RSS_1:RSS_{23})/RSS_{24}) becomes a multiplier to adjust total ventilation flow (mechanical + natural), which is proportional to RE. There may be other constraints to ventilation that could be optimized with this multi-parameter optimization approach. For instance, utilities are very concerned with minimizing HVAC loads during system generation peaks that often come in late afternoon in summer and early morning hours in winter.

A simulation tool was developed to test the algorithm's ability to reduce ventilation loads using typical meteorological year (TMY3) weather data. This enabled consideration of both backward and backward/forward differencing schemes in performing the control. The backward/forward differencing scheme assessed 24 hours of weather data in both directions, and was evaluated by imagining that the future weather forecasts of temperature and W, (perhaps made available via online weather forecast) were perfect. This exercise was also conducted with expanded backward and forward time periods. Surprisingly, all show similar ventilation load reductions—likely due to the slow change in weather patterns and an algorithm that looks back 24 hours continuously will quickly catch up with changes to current weather. Similar results were found in multiple climates, leading to the conclusion that the seasonal shape of the typical or average daily weather pattern is likely more predictive of variable ventilation savings than are short term periods. Therefore, to enhance potential for savings, seasonal adjustment factors were determined iteratively using the simulation tool to ensure the RE target is achieved. The adjustment factors considered include changes to the target ventilation flow and flow overrides based on outdoor temperature and moisture, described as follows:

$$\text{Hourly Fan Flow} = (\text{Target Fan Flow} * (\text{Average } (RSS_1:RSS_{23})/RSS_{24})$$

Where flow targets can vary as follows:

- Cooling period target if outdoor temperature > given threshold
- Heating period target if outdoor temperature < given threshold
- Floating period target if outdoor temperature is in between cooling and heating thresholds

Total ventilation flow (mechanical + natural) was initially utilized as the target, because it is inversely proportional to RE. But ultimately *mechanical ventilation fan flow* was used as the target. By capping the algorithm's output at maximum *fan flow*, this enabled any natural infiltration occurring at that time to be counted on top of the fan flow (with consideration given to interactive effects occurring with unbalanced ventilation systems). Parametric simulations allow for fine tuning of the adjustment factors to achieve a predicted annual average RE of 1.

Phase I Scheme Description and Results

Parametric simulations were conducted to arrive at an optimized set of parameters to later test in the laboratory. The resulting Phase I scheme input values are shown in Table 1. The logic for the chosen flow targets for Phase I were focused on reducing cooling energy: the 62.2.-2016 continuous fan flow value for the laboratory building was assigned for Florida's limited heating season target, but the cooling season target was dropped below the heating season target by 20 CFM. To offset the lower flow rates during warmer months, the maximum floating season flow target was set at the capacity limit of the fan. Simulation results showed temperature to be much more impactful on energy savings than moisture, so those parameters were weighted 2:1. The indoor temperature target is set intentionally below a typical thermostat set point temperature as simulations showed such a low value required to generate algorithm response that would result in cooling energy savings. The indoor W target of 12 g/m^3 corresponds to an RH of 55% at 75°F.

Table 1. Phase I scheme parameters and values

Period (defined by hourly outdoor Temp.)	Parameter	Phase I Scheme Values
Cooling	Outdoor temp. range for cooling period target	>71.5°F
	Cooling period target fan flow	55 CFM
	Outdoor temp. range for fan override (0 CFM)	n/a
Heating	Outdoor temp. range for heating period target	<60°F
	Heating period target fan flow	75 CFM
Floating	Outdoor temp. range for floating period target	<=71.5°F; >=60°F
	Floating period target fan flow	138 CFM (fan limit)
All	Indoor temp.	64.4°F
	Delta-temp. weight (X_T)	2
	Indoor moisture (W)	12 g/m^3
	Delta-moisture weight (W_W)	1

Phase I Simulation Results

Simulation results for the smart ventilation scheme chosen for Phase I, using TMY3 Orlando weather data, resulted in an average annual fan flow of 79 CFM, slightly higher than the 62.2-2016 Standard continuous fan flow requirement of 75 CFM. Hourly fan flow ranged from 17 CFM to the upper-limit of the laboratory fan, 138 CFM. Total annual average ventilation rate was 80 CFM, determined hourly by adding the modified natural infiltration to the fan component. Annual RE averaged 1.08, reaching a maximum of 2.09 for a single hour, well below the 5.00 threshold provided by the 62.2-2016 standard. While the average annual exposure is slightly higher than the desired 1.00, a compromise was struck to hedge against testing a design that might generate excessive internal moisture. The simulation results are displayed graphically in Figure 1. Hourly fan flow of the smart ventilation system is plotted in light blue with average daily RE in red. The black line represents the 62.2-2016 constant fan flow recommended for the laboratory buildings at 75 CFM and the associated RE of 1.00.

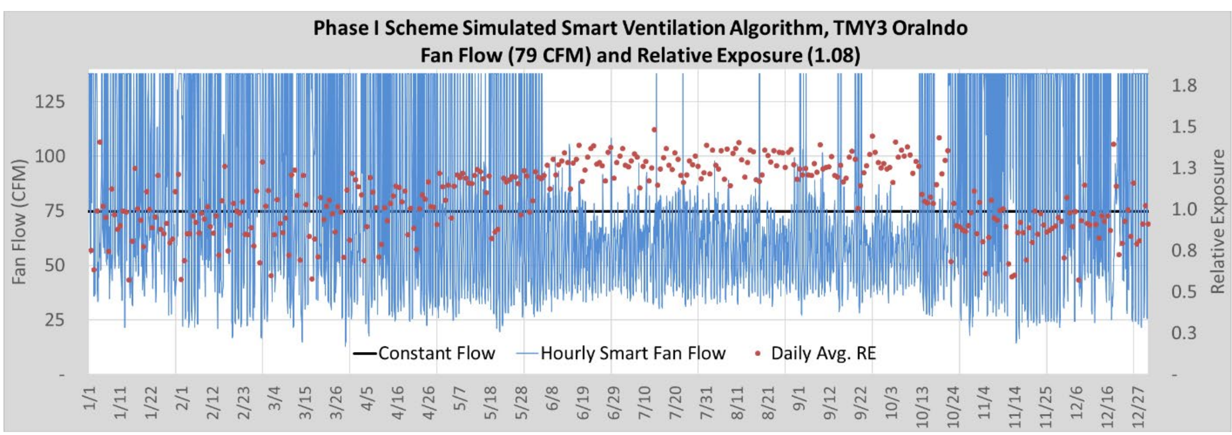

Figure 1. Phase I smart ventilation scheme simulated hourly average fan flow and daily average RE.

The plot demonstrates essentially two dominant seasons, based on the seasonal targets applied: cooling and floating. The smart ventilation algorithm creates a highly dynamic fan response, especially from mid-October through May with the fan frequently flowing at its maximum when outdoor conditions are ideal, often at night. During this floating period, average daily RE hovers near or just below 1.00. The increased floating period fan flow accommodates the restricted cooling period flow, balancing out the annual average RE, with the ultimate goal of generating cooling energy savings.

Simulated seasonal differences in sensible and latent ventilation load between the constant, or fixed fan scheme and this smart ventilation scheme are presented in Table 2. Negative numbers in the table represent heat or moisture leaving the building, positive numbers represent heat or moisture entering the building. Compared to a fixed fan, the simulation suggests that on an hourly average, the smart ventilation scheme delivers 0.20 kBtu/h less heat (reducing cooling load) and 0.31 lb/h less moisture to the building in summer. On average, more heat is also being removed during the non-summer floating hours as well, which is beneficial in the hot humid climate and could act to further reduce cooling hours later in the day by pre-cooling the building. However, during these hours more moisture is being introduced on average by the smart ventilation system (0.12 lb/h) than with the constant fan (-0.06 lb/h). Although these numbers are small, on average, the smart scheme had a negative impact on indoor moisture, which is something the Phase II scheme attempts to address. During heating hours, the smart ventilation scheme removes 0.55 kBtu/h less heat (reducing heating load) and removes 0.46 lb/h less moisture.

Table 2. Simulated ventilation load and fan power for the Phase I scheme and continuous ventilation.

Season/ Period	Sensible (kBtu/h)			Latent (lb/h)			Fan Power (Average Watts)			Average for Smart System	
	Fixed	Smart	Δ	Fixed	Smart	Δ	Fixed	Smart	Δ	Flow (CFM)	RE
Summer[a]	0.25	0.07	0.18	1.87	1.50	0.37	40	28	12	66	1.24
Non-Summer Cooling[b]	0.14	0.05	0.09	0.40	0.24	0.16	40	18	22	40	1.27
Non-Summer Floating[b]	(0.92)	(1.34)	0.42	(0.07)	1.10	(1.17)	40	50	(10)	116	0.75
Heating[c]	(2.04)	(1.58)	(0.46)	(1.80)	(1.41)	(0.39)	40	25	15	55	1.22
Annual										78	1.08

[a] The period between May 1 and Oct. 31.
[b] The hours outside of the summer period when the outdoor air temperature falls within set parameters – Cooling >71.5°F; Floating ≤71.5°F, ≥60°F.
[c] The hours when the outdoor air temperature falls below 60°F.

The changes in loads were used to estimate energy savings and are shown in Table 3. These results assume a cooling and heating system with efficiency of seasonal energy efficiency ratio 13/COP 1 (as was present in the laboratory buildings during later experimentation), 75% sensible heat ratio, and a 20% distribution loss. We implicitly assume that half of the differences in latent loads show up as increased load on the air conditioning (AC) system and the other half ends up as the observed changes to indoor relative humidity that were observed experimentally. This approximation is verified by the increase in condensate seen in the experiments as well as the modest changes in indoor moisture level. The effect of latent loads on AC electricity ends up similar in magnitude to the sensible changes seen. The change in sensible load during floating hours can be ignored, as this period is defined as hours when the outdoor temperature suggests the building should not be heating or cooling.

Fan power is also converted into energy and summed annually in the Table 3. The smart ventilation scheme saves fan energy during cooling when flows are lower, but uses more fan energy during heating and especially floating hours when flow is higher. The table shows potential for 7% annual energy savings, and over the 183-day period defined as summer in Central Florida (May 1–Oct. 31), the Phase I system is estimated to save 1.2 kWh/day versus the constant speed ventilation system.

Table 3. Simulated space conditioning energy use for the Phase I scheme and continuous ventilation.

Season/ Period	Sensible (kWh)			Latent (kWh)			Fan (kWh)			Total Savings	
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	(kWh)	%
Summer[a]	140	39	101	397	318	65	175	121	54	233	33
Non-Summer Cooling[b]	20	7	13	21	13	8	44	20	24	45	52
Non-Summer Floating[b]							117	147	(30)	(30)	-26
Heating[c]	232	180	52				12	8	4	57	23
Annual	392	226	166	418	331	87	349	296	53	305	26

[a] The period between May 1 and Oct. 31.

[b] The hours outside of the summer period when the outdoor air temperature falls within set parameters – Cooling >71.5°F; Floating ≤71.5°F, ≥60°F.

[c] The hours when the outdoor air temperature falls below 60°F

Phase I Laboratory Evaluation

Experimental work was conducted in FSEC's *Flexible Residential Test Facility* (FRTF), which features two full scale, geometrically identical side-by-side residential energy research facilities as shown in Figure 2. The slab-on-grade buildings have uninsulated concrete block walls, single pane windows, R-19 ceiling insulation, and SEER 13 air conditioners with electric resistance heat. Additional characteristics of the 1,536-ft^2 single-story buildings (volume = 13,050 ft^3) including details of the general instrumentation package and schedule and methods for simulating occupancy by generating indoor sensible and latent loads are provided elsewhere (Parker 2014). One building acted as a control, and utilized a fixed, continuous ventilation rate. The other building varied the ventilation rate with a fan operated with a smart controller created utilizing a programmable data logger.

Air leakage across the buildings' envelopes is controllable and for these experiments both buildings were set to their "tight" condition, resulting in approximately 2.2 air changes per hour at 50 Pa. Under this condition, 62.2-2016 requires 75 CFM of whole-house mechanical ventilation fan flow, which was provided to the control building continuously, on a supply basis, directly into the zone via an inline fan. The 75 CFM is determined as the fan component of total continuous ventilation required by 62.2-2016, including natural infiltration modified by use of superposition to dictate interactive effects of the desired unbalanced ventilation system, as described in the standard's Appendix C.

Figure 2. Identical buildings that comprise FSEC's Flexible Residential Test Facility.

Components of the Phase I ventilation system in each home include a Fantech FR 140 centrifugal inline fan, for which the maximum produced flow at full output was measured at 138 CFM once installed. The fan delivers outdoor air to the labs through a Continental Fan 6” iris damper and sections of 6” round metal and flex ducts insulated to R6. An airflow/pressure equation was determined using a TSI wind tunnel and flow was monitored in real-time via differential pressure readings across the damper.

While the simulations were hourly-based, the experiments controlled the fan in 15-minute increments. Variation of airflow rates in the experimental building was achieved by altering the runtime of the fixed speed inline fan with the programmable data logger as dictated by the smart ventilation algorithm. Temperature and RH are measured at the entrance and exit of the ventilation duct only while the fan is running. Indoor temperature and RH measurements were taken near the thermostat and HVAC energy measurements were recorded.

One important finding during setup for the Phase I laboratory evaluation was that the outdoor air temperature measured at the ventilation air intake under the soffit was almost always warmer than the outdoor air temperature measured at roof height. Solar heating of the east wall under the air intake contributes to this temperature imbalance. Ventilation air entering the building is even warmer due to fan heat and gains on the outdoor air duct located in the vented attic. During July and August, average temperature at roof height (15 ft), at the air intake (9 ft), and the air discharge into the building were 80.4ºF, 83.4ºF, and 84.3ºF respectively. As outdoor air temperature is an input to the smart ventilation algorithm, this has implications on the potential application of weather station data, taken at height and supplied via an internet source, on a locally operating system. To compensate for this impact during development of the Phase I scheme using TMY3 data, the target indoor temperature was set 4 °F cooler than would be otherwise selected.

Phase I Laboratory Results: 2016 Cooling and 2016–17 Floating Periods. Measured monthly energy savings for the cooling and floating periods are provided in Table 4, and average RE, fan flow, and indoor and outdoor conditions in Table 5. Results have been projected into 30-day bins because full months of data were rarely available for a variety of reasons, including disparities between the two buildings in internal gains, AC failure, complete power failure during Hurricane Matthew, and a few days requiring heating. The smart ventilation algorithm delivered 36 kWh/month or 1.2 kWh/day and 5.5% cooling energy savings for this 180-day period. Results are improved slightly, to 6.2% when fan energy is considered. Average monthly savings ranged from 1% to 17%. The smallest cooling savings were experienced during the hottest months when air delivered by the smart ventilation system was less than that of the control. As shown in Figure 3, during these months the AC ran nearly constantly and sometimes failed to deliver the indoor set point temperature of 74°F. In August, the smart building with reduced ventilation is better able to maintain desired indoor conditions (yellow) than the control (red). The control building temperature spikes about 2°F higher than smart building.

Table 4. Measured energy use during cooling and floating periods for the Phase I scheme and continuous ventilation.

Month	Cooling Energy (kWh)			Fan Energy (kWh)			Total (kWh)			
(n = days of good data)[1]	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	% Savings
Aug. (n = 21)	1,312	1,295	17	29	18	11	1,340	1,313	27	2%
Sep. (n = 15)	1,011	1,013	(2)	29	18	11	1,039	1,031	8	1%
Oct. (n = 25)	671	624	46	29	21	8	700	645	55	8%
Nov. (n = 9)	295	246	49	29	25	4	324	271	53	16%
Dec. (n = 31)	286	234	52	29	27	2	314	261	53	17%
Jan. (n = 15)	300	248	52	29	25	3	329	273	56	17%
Average	646	610	36	29	22	7	674	632	42	6.2%

[1]Daily data was averaged and extrapolated over 30 days.

Table 5. Measured environmental conditions during cooling and floating periods for the Phase I scheme and continuous ventilation.

Month (n = days of good data)	Smart Flow (CFM)	Smart RE	Outdoor OA Inlet Temp. (°F)	Control Indoor Temp. (°F)	Smart Vent Indoor Temp. (°F)	Outdoor Air Inlet Dew Point	Control Indoor RH	Smart Vent Indoor RH
Aug. (n = 21)	57	1.33	84.4	73.6	73.6	75.5	52.1	51.2
Sep. (n = 15)	59	1.31	81.5	73.6	73.9	73.5	53.1	53.9
Oct. (n = 25)	66	1.25	76.8	74.2	74.1	65.8	50.5	50.6
Nov. (n = 9)	82	1.08	70.3	74.0	74.1	60.0	50.9	53.3
Dec. (n = 31)	87	1.03	69.6	73.9	73.9	61.0	54.0	56.2
Jan. (n = 15)	82	1.06	65.3	74.3	73.9	54.0	48.3	52.8

The smart ventilation building experienced higher indoor RH during the floating period when the outside air flow is at its greatest. December experiences the highest average indoor RH for both buildings, 54.0% in the control and 56.2% in the smart. The smart building's indoor RH regularly rose between 60% and 64% during morning hours. The hours of elevated indoor RH follow the hours during which the smart ventilation building flow exceeds that of the control building. The smart building's elevated indoor RH is in response to greater ventilation rather than a buildup of internally-generated moisture that is not adequately ventilated during low-flow hours.

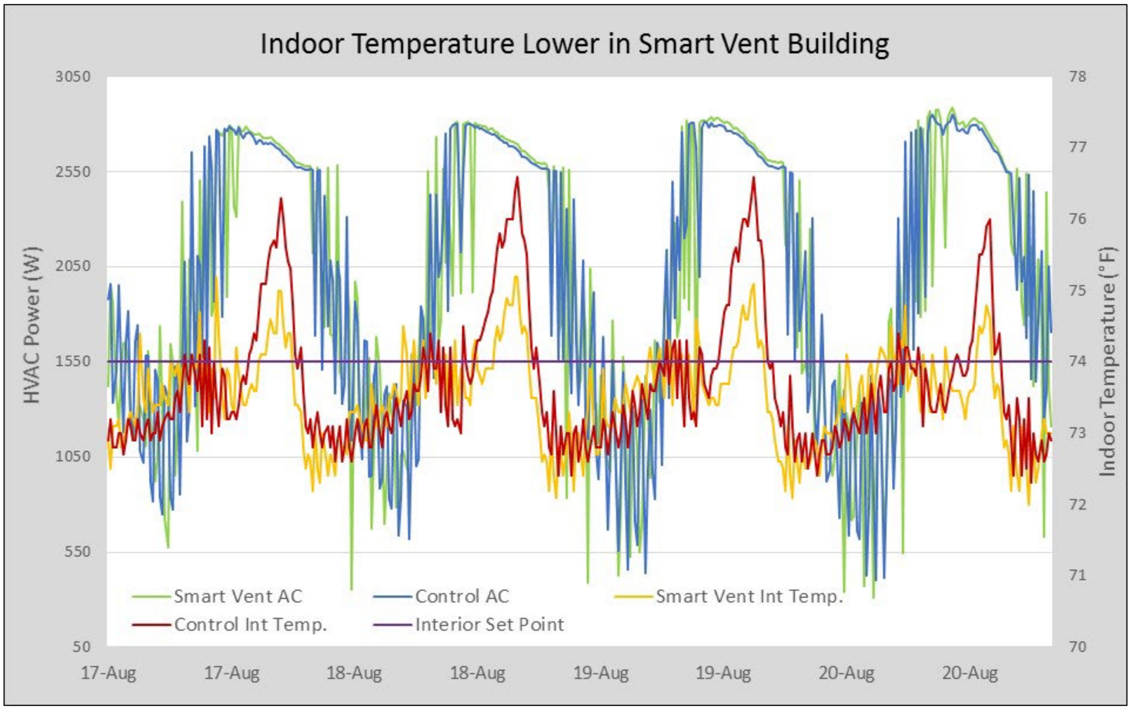

Figure 3. Measured data from August showing lower indoor temperature achieved by the Phase I scheme compared to continuous ventilation despite air conditioners running at peak capacity.

Phase I Results: 2017 Heating Period. A mild 2017 winter in Central Florida provided little data for the smart ventilation heating evaluation, offering only a handful of days with no cooling energy use and relatively substantial heating compared to floating hours. Looking at data spanning two brief cold fronts totaling 12 days found that the average fan flow for the smart ventilation building (88 CFM) exceeded that of the control (75 CFM), and RE was 0.95 given copious floating hours when the smart ventilation fan had a more aggressive flow target. Overall energy saving during these two cold fronts was -1%, with no savings from fan energy considered. With the Phase I smart ventilation scheme, the mild winter generated no savings, but provided high levels of fan flow during floating hours, helping to balance the annual RE.

Phase II Scheme Description and Results

In effort to achieve reduced RE, better energy savings, and improved indoor comfort conditions from the smart ventilation system, changes were made prior to the onset of the 2017 cooling season. A more powerful fan (*Fantech FR160* series fans) with a maximum flow of 209 CFM (tested in situ) was installed to allow greater ventilation flow during moderate outdoor conditions, and the simulation tool was revisited to test additional parameters. Based on 2016 experiences, ventilation during the hottest periods with a limited cooling system capacity led to elevated indoor temperatures that would likely not be considered favorable. Thus, a key evaluated parameter included a fan override (flow lockout) above 88°F outdoor air temperature. To compensate for a rapid increase to RE during periods of fan override, the general cooling season flow target was increased back to the ASHRAE 62.2-2016 continuous flow value. Tested scheme alterations also included methods to reduce indoor RH, including altering delta-T and delta-W weights. Ultimately, the simulation suggested the best reductions in indoor RH while maintaining savings and an annual RE of 1.0 resulted from a second floating period fan flow target of 75 cfm invoked when outdoor conditions rose above 15g/m^3 of outdoor moisture. A complete list of the Phase II scheme parameters is shown next to the Phase I scheme in Table 6.

Table 6. Phase I and II scheme parameters and values

Period (defined by hourly avg. outdoor Temp.)	Parameter	Phase I Scheme Values	Phase II Scheme Values
Cooling	Outdoor temp. range for cooling period target	>71.5°F	>71.5°F
	Cooling period target fan flow	55 CFM	75 CFM
	Outdoor temp. range for fan override (0 CFM)	n/a	>=88°F
Heating	Outdoor temp. range for heating period target	<60°F	<60°F
	Heating period target fan flow	75 CFM	75 CFM
Floating	Outdoor temp. range for floating period target	<=71.5°F; >=60°F	<=71.5°F; >=60°F
	Floating period target fan flow	138 CFM (fan limit)	209 CFM (fan limit)
	Outdoor W range to adjust floating period target	n/a	>=15g/m3
	Floating period target adjusted for W	n/a	75 CFM
All	Indoor temp. (T)	64.4°F	64.4°F
	Delta-temp. weight (X_T)	2	2
	Indoor moisture (W) Delta-moisture weight (X_W)	12 g/m3 1	12 g/m3 1

Given the lessons learned about the impact of outdoor air source on the ventilation air temperature, the algorithm was modified to trigger a fan override when the TMY3 reached 84°F and the ventilation air entering the building is assumed to be TMY3 +4°F, or 88°F. For the laboratory implementation, the fan is shut off when the outdoor air inlet temperature reaches 88°F.

Phase II Simulation Results

Simulation results for the Phase II smart ventilation scheme with TMY3 Orlando weather data suggested 96 CFM average annual fan flow, an increase from that of the Phase I scheme of 79 CFM. Total annual ventilation averaged 98 CFM. Along with the increased flow, results suggested an improved annual RE, which averaged 1.01 and reached a maximum of 3.63 for a single hour, still below the 5.00 threshold suggested by 62.2-2016. This compares with the Phase I simulation results of 1.08 and 2.09 for annual average and maximum RE, respectively.

Phase II Scheme simulation results are displayed graphically in Figure 4 with hourly fan flow of the smart ventilation plotted in light blue and average daily RE in red. The black line represents the alternative continuous fan flow at 75 CFM and associated RE of 1.00. One difference between this simulation and the Phase I version is that during the floating period, RE is more frequently below 1.00. However, a more notable difference is that during the summer season (May through October), the fan is frequently shut off, almost daily during the months of June-August.

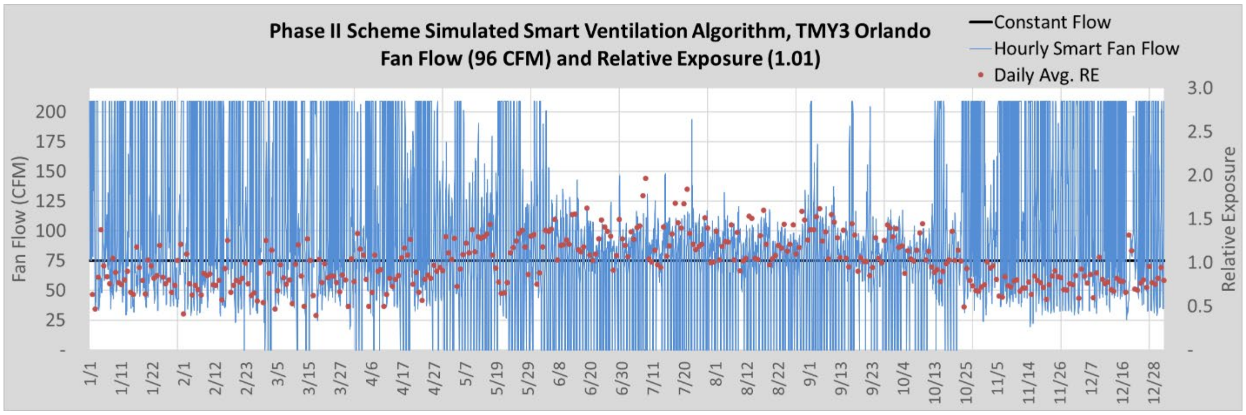

Figure 4. Phase II smart ventilation scheme simulated hourly average fan flow and daily average RE.

Simulated seasonal differences in the sensible and latent ventilation loads between the constant fan and the Phase II smart ventilation scheme are presented in Table 7. This simulation suggests the revised smart ventilation scheme reduces sensible cooling load by 0.33 kBtu/h and moisture load by 0.08 lb/h compared to the fixed scheme during the summer. The Phase II simulation also shows 0.55 kBtu/h less sensible heat removed during the heating period (reducing heating load) while more heat is removed during the floating period. While the Phase II scheme does result in moisture removal during the floating period (unlike Phase I that showed moisture addition), it is still less moisture removal on average than the fixed scheme.

The Phase II ventilation loads and fan power are converted into energy impacts using the same procedure as described for Phase I and shown in Table 8. The larger fan increased power use from 59.4 Watts to 113.8 Watts in the Phase II scheme. While it is expected that this increase in fan energy will negatively impact overall savings, the primary intent of the experiments was to investigate impact of ventilation flow modulation. In practice, fan energy use will need to be optimized, and relative impact will ultimately depend on the baseline system chosen for comparison.

Table 7. Simulated ventilation load and fan power for the Phase II scheme and continuous ventilation.

	Sensible (kBtu/h)			Latent (lb/h)			Fan Power (Average Watts)			Average	
Season/ Period	Fixed	Smart	Δ	Fixed	Smart	Δ	Fixed	Smart	Δ	Flow (CFM)	RE
Summer[a]	0.25	(0.08)	0.33	1.88	1.80	0.08	40	41	(1)	76	1.19
Non-Summer Cooling[b]	0.14	0.02	0.12	0.40	0.30	0.10	40	28	12	51	1.15
Non-Summer Floating[b]	(0.92)	(1.72)	0.80	(0.06)	(0.02)	(0.04)	40	80	(40)	147	0.66
Heating[c]	(2.04)	(1.50)	(0.54)	(1.80)	(1.34)	(0.46)	40	30	10	55	1.25
Annual										96	1.01

[a] The period between May 1 and Oct. 31.
[b] The hours outside of the summer period when the outdoor air temperature falls within set parameters – Cooling >71.5°F; Floating ≤71.5°F, ≥60°F.
[c] The hours when the outdoor air temperature falls below 60°F

Table 8. Simulated space conditioning energy use for the Phase II scheme and continuous ventilation.

Season/ Period	Sensible (kWh)			Latent (kWh)			Fan (kWh)			Total Savings	
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	(kWh)	%
Summer[a]	140	(46)	186	397	380	17	175	181	(6)	196	28
Non-Summer Cooling[b]	20	3	17	21	16	5	44	31	(13)	35	41
Non-Summer Floating[b]							117	237	(120)	(119)	-102
Heating[c]	232	170	62				12	9	(3)	65	27
Annual	392	128	264	418	396	22	349	458	(109)	177	15

[a] The period between May 1 and Oct. 31.
[b] The hours outside of the summer period when the outdoor air temperature falls within set parameters – Cooling >71.5°F; Floating ≤71.5°F, ≥50°F.
[c] The hours when the outdoor air temperature falls below 50°F.

Phase II Laboratory Results: 2017 Cooling Period

The Phase II scheme was implemented into the FRTF smart-controlled building May 1, 2017. The thermostats in both buildings were raised 2°F to 77°F since both mechanical systems had trouble meeting load demands during the hottest summer days in Phase I. The adjusted set points allow the mechanical capacity for both laboratories to better meet demand during these warmest hours. Measured monthly energy savings are provided in Table 9, and average fan flow, RE, and indoor and outdoor conditions in Table 10. Results have been projected into 30-day bins, as a full month of data were not available because of internal gains issues—either disparities between the two buildings or limited generation in both. Although the results are limited to three months, the smart ventilation algorithm with the modified scheme and more powerful fan delivered savings far superior to the prior scheme, generating measured 12.4% AC savings in May (89 kWh/month, 3.0 kWh/day), 8.8% in June (73 kWh/month, 2.4 kWh/day), and 8.7% in July (88 kWh/month, 2.9 kWh/day), averaging 9.8% AC savings for the total period. Factoring in fan energy use, the savings are reduced slightly to 9.6% (84 kWh/month, 2.8 kWh/day). While the months of measured data varied between phases, the average cooling energy savings for three months under Phase I was only 2.9%.

Table 9. Measured energy use during cooling and floating periods for the Phase II scheme and continuous ventilation.

Month	Cooling Energy (kWh)			Fan Energy (kWh)			Total Energy (kWh)			
(n = days of good data)[1]	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	% Savings
May (n=22)	719	630	89	29	36	(7)	748	666	82	11.0%
Jun (n=22)	822	749	73	29	20	8	851	770	81	9.5%
Jul (n = 26)	1,012	924	88	29	26	2	1,040	950	90	8.6%
Average	851	768	83	29	27	1	880	795	84	9.6%

[1]Daily data was averaged and extrapolated over 30 days.

Table 10. Measured environmental conditions during cooling and floating periods for the Phase II scheme and continuous ventilation.

Month (n = days of good data)	Smart Flow (CFM)	Smart RE	Outdoor OA Inlet Temp. (°F)	Control Indoor Temp. (°F)	Smart Vent Indoor Temp. (°F)	Outdoor Air Inlet Dew Point (°F)	Control Indoor RH	Smart Vent Indoor RH
May (n=22)	91	0.99	76.4	76.0	75.9	39.6	49.1	50.4
Jun (n=22)	71	1.10	80.3	76.0	76.2	60.0	52.3	52.4
Jul (n = 26)	67	1.27	83.0	76.0	76.1	61.3	49.0	49.3

The average indoor relative humidity in May was slightly higher in the smart building than the control, but overall the RH in the smart ventilation building was more closely aligned with that in the constant flow building than it was in Phase I. Still, floating season has yet to be evaluated, which is when the RH difference between the buildings was greatest during Phase I. Similarly, a full year of data would be needed to evaluate how well the Phase II scheme actually succeeded in attaining the 62.2-2016 RE target.

The average daily profile for June is highlighted in Figure 5, with ventilation scheme savings at 11.3%. The increased fan flow in the smart ventilation building during the morning hours has little impact on relative humidity while still achieving impressive energy savings. The AC energy savings of the smart ventilation scheme are more pronounced during midday, when the outdoor temperature rises and the smart fan flow is greatly reduced.

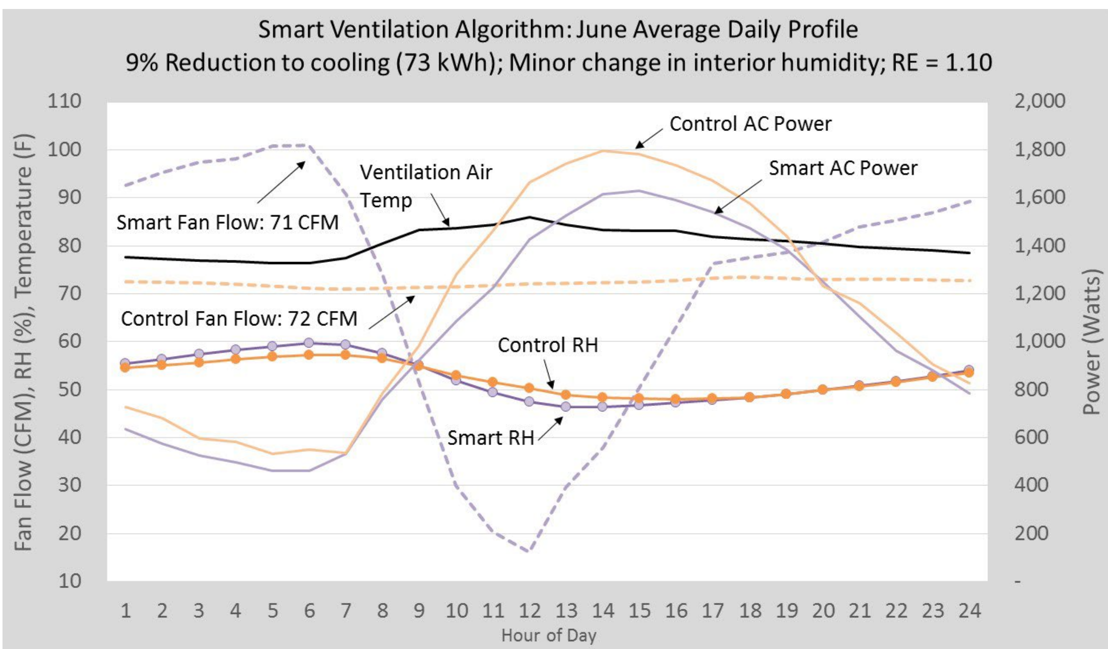

Figure 5. The June average day profile represents a summary of Phase II scheme performance.

Simulated Results for Other Climates

To estimate the ability of the smart ventilation algorithm to reduce space conditioning energy in other climates, whole building energy simulations were conducted. The National Renewable Energy Laboratory's (NREL) BEOpt software, which uses the US Department of

Energy's (DOE) EnergyPlus simulation engine was used for this purpose. NREL provided a customized input capability for BEOpt version 2.6.0.1 that allowed for hourly specification of total infiltration rate and fan energy. The FSEC FRTF laboratory was modeled to serve as the test building, with a few changes to envelope and mechanical system components to create a single building representative of average new construction in different climates. These include 2x6 frame wall insulated to R-19, R-38 ceiling insulation, double pane low-e windows, a SEER 16/HSPF 8.6 heat pump, and a balanced ventilation system with no heat recovery.

Hourly total infiltration rate and fan energy were obtained using the FSEC algorithm simulation tool. TMY3 data was input for each of five representative climates, and algorithm parameters adjusted to ensure RE compliance. The parameters used for each climate are identical to the Phase II scheme values shown in Table 6, except for target flows and high/low temperature flow lockouts that were determined iteratively for each climate. The lockout procedure for warm climates identified the lowest outdoor temperature at which the fan could be turned off during cooling, while maintaining an annual average RE of 1.0. Then the highest outdoor temperature at which the fan could be turned off during heating without negatively affecting RE was found. The opposite procedure was utilized for cold climates. The 62.2-2016 continuous mechanical ventilation flow for each climate was assigned for heating and cooling flow targets, and the 209 cfm flow limit of the Phase II laboratory fan was assigned for the floating target. Table 12 shows the simulated space conditioning energy for each climate modeled, along with the flow target used. Results show that across a variety of climates, space conditioning savings of > 5% can be achieved with the simple approach used to set algorithm parameters. While increased fan energy for the smart ventilation scheme erodes savings, additional optimization of the fan choice could help maximize savings.

To arrive at a design procedure that could be used to apply the smart ventilation algorithm in any climate, regression analysis was performed utilizing the iterated flow targets, heating and cooling degree days (HDD, CDD), and the 97.5% summer and winter (Tds, Tdw) design temperatures for each climate. Table 13 compares the iterated high and low temp locks to the regressed values Resulting equations for the low temp lock (Tl,l) and high temp lock (Tl,h) are as follows:

$$Tl,l = -22.0 + 1.36(Tdw) + 4.8(HDD/CDD);\ R^2 = 0.92$$

$$Tl,h = -2.45 + 0.93(Tds) = 0.88(HDD/CDD);\ R^2 = 0.98$$

Table 12. Heating/cooling flow targets and resulting relative exposure and energy savings for multiple climates.

Location	Heating/Cooling Flow Target (cfm)	Annual Average RE	Max Hourly RE	Annual Space Conditioning Energy Savings (kWh/%)	Annual Space Conditioning Energy + vent fan Savings (kWh/%)
Orlando, FL	66	1.0	3.6	211 / 8.0	155 / 5.2
Atlanta, GA	64	1.0	3.6	182 / 5.4	117 / 3.2
Minneapolis, MN	60	1.0	3.2	777 / 5.8	753 / 5.5
Chicago, IL	61	1.0	3.2	621 / 6.9	592 / 6.3
Phoenix, AZ	65	1.0	3.3	311 / 6.8	229 / 4.6

Table 13. Regression parameters to determine high and low temp lockouts for multiple climates.

Location	Iterative High Temp Lock (ºF)	Iterative Low Temp Lock (ºF)	HDD/CDD	Heating/Cooling 97.5% design temp (ºF)	Regression High Temp Lock (ºF)	Regression Low Temp Lock (ºF)
Orlando, FL	85	42	766 / 3564	38 / 93	84	42
Atlanta, GA	83	17	2961 / 1883	22 / 92	84	22
Minneapolis, MN	90	8	8382 / 753	-12 / 89	90	12
Chicago, IL	87	15	6639 / 843	-4 / 89	87	9
Phoenix, AZ	97	39	1765 / 4607	34 / 107	97	36

Conclusions

An algorithm for smart ventilation control was developed that interprets measurements of outdoor temperature and moisture and varies ventilation to minimize sensible and latent load impacts. Simulations were conducted to tune the algorithm with differing flow targets and seasonal adjustment factors to maximize heating and cooling energy savings compared to continuous ventilation, maintain similar indoor RH, and achieve RE with respect to 62.2-2016. The second of two schemes evaluated suggested that compliant annual average and acute RE could be maintained with ventilation sensible and latent load reductions during cooling conditions of 73%and 9% respectively. To achieve these savings, ventilation flow is reduced during cooling weather, and elevated ventilation air flow during the floating period is necessary to maintain annual average RE. Simulations show this approach is likely to increase net moisture addition during the floating period over continuous ventilation; however, experimentation indicates the impact on indoor RH during this time is minor.

A ventilation system controlled by the algorithm was implemented in a laboratory home and tested side by side with an identical home operating with continuous mechanical ventilation. Average cooling energy savings of 10% were measured during the first three months of evaluation due to the reduction in sensible and latent load created by the advanced system. A fan with a maximum capacity nearly three times greater than the continuous fan was required to achieve these savings, and added fan energy needs to be carefully considered so as not to erode potential cooling savings. The negative impact of increased fan power on the savings of the scheme suggests that the use of permanent magnet motors with much lower power would be highly beneficial to both the ability to modulate flow over periods, rather than utilize a fixed fan speed for varying amounts of time, as well as to reduce fan electric power consumption.

Experimental testing utilized sensor-based measurements of occupancy and weather parameters collected at the actual test homes, but commercialized systems could leverage both weather data available from internet connected devices such as smart thermostats. One lesson learned is if such weather data is used as an element of control, algorithms may need to be tuned to correct for local anomalies.

Whole building energy simulations were conducted and predict at least 5% space conditioning energy savings across differing climates, once the ventilation fan is optimized for energy savings. Regression analysis identified a simplistic design procedure enabling the smart ventilation algorithm to be applied in any climate.

Acknowledgements

This report summarizes research funded by the U.S. Department of Energy (DOE), Office of Energy Efficient and Renewable Energy, Building America Program. The support and encouragement of Program staff is gratefully acknowledged. The authors would also like to thank Chuck Withers and Dave Chasar of the Florida Solar Energy Center (FSEC) for implementing the smart ventilation control in the FSEC test laboratories.

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