Practical Applications and Case Study of Temperature-Based Smart Ventilation Controls

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ABSTRACT

Smart ventilation controls (SVC) provide energy and indoor air quality (IAQ) advantages through dynamic real-time control of mechanical ventilation rates. ASHRAE Standard 62.2-2013 (Section 4.6) allows for such alternate SVC strategies, if equivalent annual pollutant exposure is provided. This paper presents results from U.S. Department of Energy (DOE) Building America (BA) program stakeholder collaborations on temperature-based smart ventilation control (TSVC) as one potential option. Unlike the "continuous" ventilation typically implemented to meet ASHRAE Standard 62.2-2013, temperature-based ventilation controls take advantage of the dynamics of stack infiltration, which varies with weather, house height, and envelope leakage. TSVC strategy turns off mechanical ventilation at times of large temperature difference and moves ventilation to periods with smaller temperature differences. To ensure equivalent annual pollutant exposure, mechanical airflow rates must be increased for temperature-based systems. In this paper, we compare the energy and IAQ performance of a temperature-based ventilation control that shuts the fan off at a specified single cut-off temperature to a continuously operated ventilation system fan that is sized to comply with ASHRAE 62.2-2013. This paper presents simulation analysis results using two simulation tools: 1) REGCAP and its advanced ventilation model for detraining ventilation TSVC equivalency, 2) A new beta version of EnergyGauge® USA for estimating energy savings. Relative humidity (RH), carbon dioxide (CO_2) concentrations, and energy use are presented for two occupied case study homes in cold and marine climates involving weekly "flip flop" tests between continuous and single temperature cutout control scenarios. Preliminary investigations of market costs and modeled energy savings suggest quick simple paybacks from TSVCs for these case study homes. An additional potential benefit of SVC is user acceptance. Many residents do not like to use ventilation unless they perceive that the air quality is poor, despite the fact that many contaminants cannot be sensed by occupants. Providing options that residents believe is taking dynamics into account may contribute to wider acceptance of beneficial ventilation.

BACKGROUND

Residential energy-efficient construction has focused on tighter envelopes to save energy; however, this also creates a potential for under-ventilation and compromised IAQ (Offermann 2009). The purpose of ventilation is to remove contaminants generated inside a space, preferably to levels constituting "good" IAQ. ASHRAE Standard 62.2 assumes that there will be a constant ventilation rate from a purpose-provided

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mechanical ventilation system, for every hour of the day, with guidance for intermittent system operation. Ventilation fans are usually operated for 24 hours per day at the same rate regardless of the natural infiltration rate. These continuous systems ignore the variability of weather-driven natural infiltration, which can lead to excess ventilation during cold periods and unnecessary energy expense. Weather-driven natural infiltration through openings in the building envelope is caused by pressure differences due to indoor-outdoor temperature differences ("stack") and wind. The magnitude of infiltration depends on many factors, including environmental conditions, building tightness, and building geometry. This SVC in this study evaluated the concentrations of pollutants for a time-varying ventilation system controlled by temperature relative to the same house with a constant ventilation flow rate. The SVC temperature controller turned off the whole house ventilation fan when outdoor temperatures were below a predetermined level that was calculated based on the contribution of stack effect infiltration to the house ventilation. The controller was evaluated using simulations and field demonstrations in two homes.

REGCAP VENTILATION EQUIVALENCY MODELING

Lawrence Berkeley National Laboratory (LBNL) has performed detailed simulation studies of combined energy and IAQ performance in residences. This work has primarily relied on the REGCAP simulation tool, which combines models for mass-balance ventilation (including envelope, duct, and mechanical flows), heat transfer, HVAC equipment, and moisture. Simulations are performed at one-minute time resolution to allow for dynamic HVAC system operation and use of real-time ventilation controllers. Details are presented elsewhere (Walker et al. 2005; Walker and Sherman 2006; Walker 1993). Recent work has developed the concept of ventilation equivalence (Sherman et al. 2011), which can be used to ensure that variable ventilation rates give the same pollutant exposures as constant ventilation rates. LBNL simulated the performance of temperature-based smart ventilation controllers (TSVC) in two prototypical test homes across U.S. climate zones, with varying envelope airtightness and numbers of stories (Less, Walker, and Tang 2014). The simulations compared energy and IAQ performance of a TSVC to a base case of a continuously operated ventilation fan sized to comply with ASHRAE 62.2-2013 (ASHRAE 2013) whole-house (WH) ventilation requirements, including ASHRAE 62.2-2013 infiltration credit. The LBNL simulations of the simple TSVC satisfied ASHRAE 62.2-2013 by ensuring that annual pollutant exposure was equivalent between the dynamic temperature-controlled and continuous fan cases. In order to obtain equivalence the WH ventilation fan must have higher flow during times of operation to make up for shortfalls in ventilation when it is turned off. The simulation results were used to find the required WH mechanical ventilation system over-sizing relative to ASHRAE 62.2 requirements for continuous systems. This required an iterative approach because the required fan oversizing depended on the control strategy and specific temperature cutoff.

These simulations considered only annual ventilation equivalence. Short-term fluctuations were not controlled for, such that acute exposures may present some health concerns. While annual values represent "chronic" or long-term exposures, short-term peaks in pollutant levels can also present "acute" risks to occupant health. For example, during extended periods of low outside temperature, the ventilation system may have been continuously off for long periods of time. Ventilation was operated at a higher airflow during warmer periods of the year to ensure annual equivalence, but pollutant levels could have reached unacceptable short-term levels during the off periods. The REGCAP simulation results showed that acute issues only occur for tight homes (<1.5 ACH50) in mild climates, and even then, not under the single temperature cutoff control used here. The simulations also showed that the homes and control strategies susceptible to acute issues were situations that were not suitable for temperature control – because the tight envelope and/or mild climate meant that there is little stack driven air flow and therefore little opportunity to turn off the whole house fan. Similarly, for very leaky homes (>10 ACH50) the operation of the whole house fan has very little effect on total ventilation. The envelope leakage range that has the biggest savings opportunity using temperature controlled SVC is 5-7 ACH50.

In our temperature-based work, these concerns should be mitigated by the fact that periods of low temperature are associated with higher natural infiltration due to stack pressures. It is also notable that acute pollutant exposures in homes are typically caused by occupant activities that release large quantities of pollutants over a short period of time, such as cooking or cleaning. Marginally lower or higher continuous ventilation rates will have little effect of these localized events.

In light of these acute exposure concerns, ASHRAE Standard 62.2 has now adopted a change for ventilation equivalence which includes a maximum pollutant exposure value (C_{max}) that smart controllers can use to provide annual equivalence while also protecting against acute hazards. TSVC approaches that guard against unacceptable acute exposures may result in some minimum amount of hourly or daily ventilation system run-time, or other provisions, all of which might reduce predicted energy savings for TSVC. As noted above, the TSVC controllers in this project did not explicitly include a C_{max} limit.

ENERGYGAUGE USA™ ENERGY MODELING AND SIMPLE PAYBACK OF TSVC

Using the TSVC strategies assessed by LBNL, the EnergyGauge USA software was used with new beta features to assess potential energy savings for the advanced controls. Simulation test cases were developed that reflect the field-tested homes. An EnergyGauge USA analysis was employed to estimate the energy use of TSVC as compared to continuous operating systems in these example homes. Baseline cases with continuous WH exhaust fans were sized per ASHRAE 62.2-2013 (with infiltration credit). The two test homes using TSVC used over-sized WH exhaust fans, and the installed airflow rates were used in conjunction with the iterative fan-sizing calculations discussed above to identify custom cut-off temperatures with the highest anticipated energy savings. These cut-offs are different from those used in the LBNL modeling described above. House parameters used in EnergyGauge USA modeling are summarized in Table 1.

Table 1. ASHRAE 62.2 Ventilation/Infiltration Parameters, Requirements, Energy Savings, and Simple Payback

Location	ACH_{50}	CFM_{50}	CFM	CFM	TSVC Off > °F (°C)	TSVC \$/year saved[1]	TSVC Payback
Champaign, IL 2 story, 900 ft^2	9	1,073	30	80	55	\$7.30	11 year
Olympia, WA 2 story, 1,640 ft^2	5	1,152	40	90	57	\$23.00	4 year

[1] Assumes 0.10/kWh and \$1.00/therm. TSVC assumed to have a retail installed cost of \$80.

WA Case Study: The Howard residence test house (hereafter referenced as the "WA home" is a two-story, 1,640 square foot historical house located in Olympia, Washington. It underwent a deep energy retrofit in 2010 that significantly upgraded the building envelope and reduced the air change rate from 20 ACH_{50} to 5 ACH_{50}. Space conditioning is provided by a 1-ton single head ENERGY STAR (HSPF=12, SEER 25) ductless heat pump (DHP) with the indoor unit located on the first floor. The TSVC outdoor temperature sensor was located outside the bathroom behind the DHP outdoor unit. The WH exhaust fan with TSVC was located in the first floor bathroom. During the weekly flip flop testing in the TSVC mode, the WH fan operated at 90 CFM whenever the outside temperature was above 57°F (14°C), and was turned off below this temperature. During the ASHRAE 62.2-2013 mode, the WH exhaust fan ran continuously at 40 CFM regardless of outside temperature. EnergyGauge USA analysis suggested that for the WA home, the energy savings from enacting the cutoff strategy is estimated at \$23/year of the HVAC energy use, as shown in Table 1. Table 1 also provides a 4 year simple payback estimate, assuming a cost to the consumer of \$80, based on TSVC costs of \$20 for the temperature relay control, and \$60 labor for electrician wiring to WH fan. This simple payback is well within the expected useful life of the TSVC.

IL Case Study: The test home in Champaign, IL (hereafter referred to as the "IL home") is a singlefamily one-story home on a full unoccupied and unfinished basement. The home is 900 square feet. Blower door tests measured the home at about 9 ACH_{50}. The WH exhaust fan was installed in the bathroom. The TSVC outdoor temperature sensor was located in the gable vent of the attic. During the weekly flip flop testing in the TSVC mode, the WH fan operated at 80 CFM whenever the outside temperature was above 55°F (13°C), and was turned off below that temperature. During the ASHRAE 62.2-2013 mode, the WH exhaust fan ran continuously at 30 CFM regardless of outside temperature. EnergyGauge USA analysis suggested that the energy savings from enacting the cutoff strategy is estimated at $7.30/year of the HVAC energy use, as shown in Table 1. Table 1 also provides a simple payback estimate, assuming the same cost to the consumer of $80. This simple payback is well within the expected useful life of the TSVC.

FIELD MONITORING RESULTS

Field monitoring was also used to verify the energy and indoor environmental performance of TSVC developed through LBNL simulations described above. One primary question addressed by the field-testing was whether the fan control operated as intended. Two issues are considered: 1) fan cycling, and 2) whether the temperature control is working properly. The case studies suggest that the TSVC seems to operate as intended in both the WA and IL homes. Another primary question is to determine how the operation of the TSVC impacts the homes' CO_2 concentration and RH.

CO_2 – WA Home

The highest CO_2 levels in the WA home when all windows were closed were 2,200 ppm (there were some isolated higher levels in the second bedroom). This is above the suggested level of 700 ppm above outdoor conditions that is a "proxy" for inadequate ventilation, but is well below concentrations of concern for cognitive function. Levels of CO_2 tended to be higher with TSVC, particularly at lower temperatures. In the main living area, during TSVC operation the average CO_2 level was 60 ppm higher than continuous operation. This difference increased to 100 ppm for outdoor temperatures below 55ºF (13ºC). For the master bedroom these values were 90 ppm and 140 ppm respectively and for the second bedroom 100 and 220 ppm. Above 60ºF (16ºC), the CO_2 levels in TSVC mode should be lower because of higher ventilation from fan operation at 90 cfm instead of 40 cfm. However, this is not the case. While the differences are smaller, the average CO_2 levels are 20, 50, and 40 ppm higher in TSVC mode in the main living area, master bedroom, and second bedroom. This is likely due to differences in occupancy, air mixing and some window opening during the summer period. The small differences in CO_2 levels during all conditions for the two modes of operation suggest that other influences on CO_2 were greater than the control mode. Note that although no discernable differences were found by using SVC for CO_2, CO_2 is only a guide for occupant generated pollutants, and study of other non-occupant related pollutants (such as formaldehyde) should be conducted in the future.

CO_2 – IL Home

The highest CO_2 levels measured during periods when all windows were closed in the IL home were just above 1,600 ppm, which is above the "proxy for inadequate ventilation noted above, but is not at a level of concern for cognitive function. CO_2 levels tended to be higher with temperature-based ventilation control at lower temperatures. A two-sample t-test shows that the difference is statistically significant, with the temperature-based control being statistically higher (average 966 ppm) than the continuous ventilation (average 868 ppm) at the 95% confidence level (p=0.0038). For data above 55ºF (13ºC), the two-sample t-test shows that there is a reduction in CO_2 with the temperature-based control (average 643 ppm vs. 692 ppm for continuous fan operation), which is not quite statistically significant at the 95% level but is at the 90% level (p=0.0592). As is the case for the WA home, the differences in CO_2 levels between the two operation modes are small relative to other influences. We might expect greater variation in CO_2 with TSVC operation, and this tends to be the case. Further study regarding other non-occupant related contaminants in the two modes of operation is needed.

Humidity

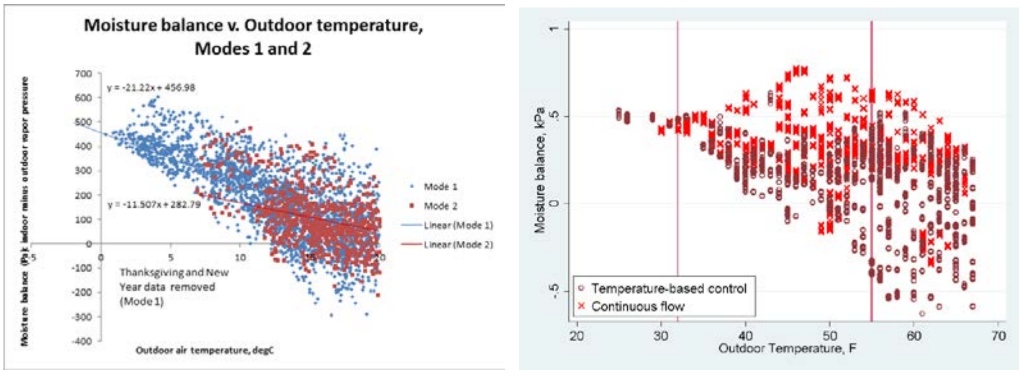
Analysis of humidity is not straightforward for a variety of reasons, including that RH is temperature-dependent, outdoors can be a significant source, and there can be significant storage in building materials and furnishings. The first two of these issues can be addressed by using the "moisture balance" technique (Francisco and Rose 2010). This technique, also used by IEA Annex 41 in the development of ISO 13788 (IEA, 2008), compares the indoor vapor pressure (which is temperature-independent) to the vapor pressure outdoors over a range of outdoor temperatures. The analysis is conducted by performing a linear regression on the vapor pressure difference vs. outdoor temperature between 32°F (0°C) and 68°F (20°C), with the regression fixed at 0 at 68°F (20°C). The intercept at 32°F (0°C) is the value used to characterize the home's vapor pressure excess, with higher values corresponding to damper buildings.

Figure 1 and Figure 2 show the hourly data from the IL and WA homes, respectively, for temperatures of 68°F (20°C) and colder. A number of points have negative values, indicating that there was more moisture in the outdoor air than in the indoor air.

The IL analysis found that with the temperature-based control, the vapor pressure excess was 234 Pa; for continuous ventilation, the vapor pressure excess was 586 Pa. These differences are statistically significant at the 95% confidence level. The difference is largely attributable to the data in the 44ºF to 54ºF (7°C to 12°C) range, when the temperature-based control turned the ventilation fan off and, therefore, did not bring in additional cool (and likely dry) outdoor air or exhaust indoor air. This suggests that occupant behavior was different during the two control strategies, and that the apparent difference was due to other factors that were undocumented.

The WA analysis found that with the temperature-based control, the vapor pressure excess was 616 Pa; for continuous ventilation, the vapor pressure excess was 472 Pa. Qualitatively the direction of this change is as expected.

Figure 1a & 1b. Vapor Pressure Excess vs. Outdoor Temperature for IL & WA



CONCLUSIONS & RECOMMENDATIONS

The field-testing of TSVC successfully demonstrated "proof of concept" and viability of simple controls in two weatherized homes where WH mechanical ventilation systems were installed as part of the retrofit. One home was located in the marine climate of Olympia, WA, and the other was in the cold climate of Champaign, IL. Data were collected in 2015-16. During this monitoring period, the research plan employed "flip flop tests," which varied the WH ventilation system between continuous operation per ASHRAE and outside temperature-based operation.

The TSVC prototype control is estimated to cost less than $80, and it functioned as intended to control the ventilation system lockout at the targeted temperature, based on actual field conditions in the WA and IL case studies. Two case study findings suggest:

1. TSVC device for the marine and cold climate test homes is estimated to save as much as $7.30-$23.00/year based on EnergyGauge USA modeling. Given the low first cost of the system and its modeled energy savings, a large potential market may exist in retrofit and new homes.
2. The impact of the TSVC on CO_2 and humidity was not significant compared to other factors, for example occupancy, window opening, and wind effects.

ACKNOWLEDGMENTS

The authors would like to acknowledge the following individuals who contributed to this effort.

- Committee members of ASHRAE Standard 62.2 committee
- Gary Nelson – The Energy Conservatory
- Don Stevens – Panasonic USA
- Luke Howard and Melinda Spencer – Washington State University Energy Program
- Eric Martin and David Beal – Florida Solar Energy Center
- Eric Werling – U.S. DOE BA

REFERENCES

ANSI/ASHRAE 2013. *Standard 62.2-2013 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.* ASHRAE. Atlanta, GA.

Francisco, P. and W. Rose 2010. "Temperature and Humidity Measurements in 71 Homes Participating in an IAQ Improvement Program." *Proceedings of Thermal Performance of Exterior Envelopes of Whole Buildings XI*, December.

IEA ECBCS Annex 41 2008. *Proceedings of the Closing Seminar*. Copenhagen, June 19, 2008 (C. Rode, editor), Dept. of Civil Engineering, BYG R-191, Technical University of Denmark, Kgs. Lyngby, Denmark.

Less, B., I.S. Walker, and Y. Tang 2014. *Development of an Outdoor Temperature-Based Control Algorithm for Residential Mechanical Ventilation Control* (No. LBNL-6936E). Berkeley, CA: Lawrence Berkeley National Laboratory. Offerman, F. J. 2009. *Ventilation and Indoor Air Quality in New Homes*. PIER Collaborative Report, California Energy Commission & California Environmental Protection Agency Air Resources Board.

Sherman, M. H., I. S. Walker, and J. M. Logue. 2011. Equivalence in Ventilation and Indoor Air Quality. LBNL-5036E. http://eetd.lbl.gov/node/51446

Walker, I. S. 1993. *Attic Ventilation, Heat and Moisture Transfer*. University of Alberta, Edmonton, Alberta.

Walker, I. S., T.W. Forest, and D.J. Wilson 2005. An attic-interior infiltration and interzone transport model of a house. *Building and Environment*, *40*(5), 701–718. http://doi.org/10.1016/j.buildenv.2004.08.002

Walker, I. S., and M.H. Sherman 2006. *Evaluation of Existing Technologies for Meeting Residential Ventilation Requirements* (No. LBNL-59998). Berkeley, CA: Lawrence Berkeley National Laboratory.