

Vent Right and Then? Mechanical Ventilation, Dehumidification and Energy Use in Humid Climates

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ABSTRACT

The desirability of mechanical ventilation in homes and acceptable infiltration rates are sometimes contentious topics – particularly in humid climates. We present preliminary results of two monitored lab homes constructed to represent the thermal characteristics of typical existing Florida homes. They are configured for the ventilation study with tight and leaky envelopes and with and without mechanical ventilation. We also present simulation results of high performance new homes with mechanical ventilation and typical older existing homes with and without air tightening and mechanical ventilation to provide added context.

Lab home test results indicate that mechanical supply ventilation of the tight home (2 ach50) in accordance with ASHRAE 62.2-2013 increased average indoor relative humidity by 2.2% as compared with the leaky home (8 ach50) without mechanical ventilation in the hot, humid climate of central Florida. However, cooling energy use was increased by about 27% due to substantially increased air conditioner moisture removal (>63%). Results also indicate that failure to ventilate the tight home during winter results in excessive indoor relative humidity due to typical internal moisture gains.

To explore other conditions and climates, highly-efficient new tight homes (1.5 and 3 ach50) were simulated in twelve TMY3 weather files representing five U.S. climate zones. Existing leaky homes (11 ach50) were also simulated for one TMY city. Parametric analysis was accomplished using different ventilation system types with and without dehumidification.

Background

New model building codes (IECC 2012) require that new homes be tested to have reduced envelope leakage rates of 5 ach50 in IECC climate zones 1-2 and 3 ach50 in IECC climate zones 3-8. Additionally, the International Mechanical Code (IMC 2012) requires that these homes be mechanically ventilated. Further, the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE) operate high-performance building programs that require that new homes be ventilated in accordance with ASHRAE 62.2 to qualify for their programs. Additionally, envelope tightening is usually recommended as an efficiency strategy for retrofitting existing homes. For example, the energy.gov website (2012) has a link from its main page to air sealing that recommends sealing and mechanical ventilation.

DOE Building America program teams have anecdotally reported that builders in southern humid climates are reluctant to fully comply with ASHRAE 62.2 due to concerns with indoor moisture control and homeowner call backs. Rudd and Lstiburek (2008) review some of the issues facing mechanical ventilation ranging from first cost to poor air distribution and high energy use. ASHRAE Research Project 1449 conducted simulation research that showed that the hours when indoor RH exceeds 60% in high-performance homes in southern, humid climates can exceed 2000 hours per year (Rudd et al. 2013). The 60% RH threshold used in these analyses may be somewhat arbitrary for hot, humid climates because it is based principally on the RH that

could potentially result in wall or floor surface condensation in winter in northern climates. In hot, humid climates like Florida, 60% indoor RH is unlikely to result in wall or floor surface condensation so questions remain as to the value that should be used in these climates as a threshold that is indicative of potential moisture control problems.

Clearly, ventilation issues are climate dependent, presenting different problems in hot, humid climates than in cold or dry climates. ASHRAE 55-2013 on Thermal Environmental Conditions for Human Occupancy intends that indoor dew point temperatures be maintained below 62 °F. The operating characteristics of typical air conditioning equipment is such that indoor dew point temperatures are normally near 55 °F during the summer air conditioning season. In hot, humid southeastern and gulf coast climates where summertime outdoor average dew point temperatures reach 75 °F, ventilation can introduce significant quantities of excess moisture into homes, presenting indoor comfort and moisture control issues that do not exist in other climates.

As part of a long-term experiment, the impacts of infiltration and mechanical ventilation are being studied in side-by-side laboratory homes in central Florida as part of the DOE Building America program. This paper reports on preliminary winter and summer laboratory home results from a leaky home (8 ach50) without mechanical ventilation and a tight home (2 ach50) with and without mechanical ventilation. It also presents results from building simulations employing different envelope leakage and ventilation strategies.

Leaky vs. Tight Laboratory Experiments

The Facility

Two reconfigurable, geometrically identical, full-scale, side-by-side residential building energy research facilities at the Florida Solar Energy Center (FSEC), as shown in Figure 1, are being used to conduct research experiments. The Building America Partnership for Improved Residential Construction (BA-PIRC) uses these facilities to conduct research on advanced building energy efficiency technologies under controlled conditions. Each home has conditioned space of 1536 ft² of uninsulated concrete block construction with single-pane windows. Further details of the homes are provided by Vieira and Sherwin (2012).

A series of natural and mechanical ventilation studies have been conducted in these facilities (Vieira, et al. 2013; Parker, et al, 2014). The envelope leakage is carefully controlled such that one home has tested envelope leakage of 2 ach50 and the other has tested envelope leakage of 8 ach50. Both homes are unoccupied but are equipped to provide both sensible and latent internal gain using standard occupancy profiles (ANSI/RESNET 2014, see also Parker et al. 2010). Because the homes are unoccupied, it was possible to use CO₂ as a tracer gas to measure air exchange with the outdoors. A constant CO₂ injection rate using mass flow controllers was employed for this purpose. CO₂ concentrations were measured every 10 seconds, along with energy use, temperatures and relative humidities. CO₂, temperature and relative humidity data were averaged over 15-minute increments and energy use was summed.

Winter Results

For the first winter period (January 2012), the tight and leaky lab homes were operated without mechanical ventilation. As shown in Figure 1, temperatures were mild with two cold spells. Temperatures inside the two laboratories remained similar, as shown in Figure 2. Note

that during warm days, the temperature increased beyond the winter set point. The heating thermostat was set to 72 °F and cooling was turned off during this test.

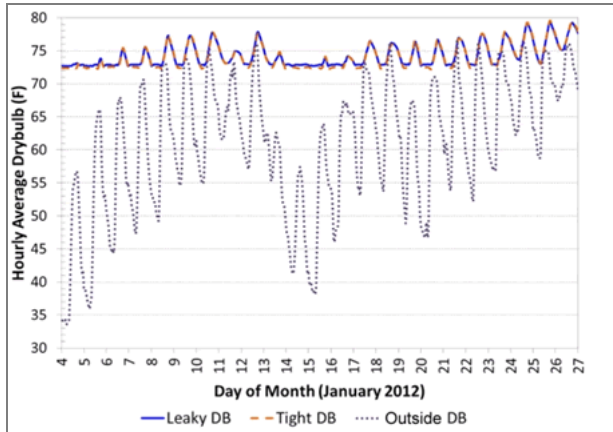


Figure 1. January outdoor air (Outside DP) and indoor air dry bulb temperatures for leaky home (Leaky DB) and tight home (Tight DB).

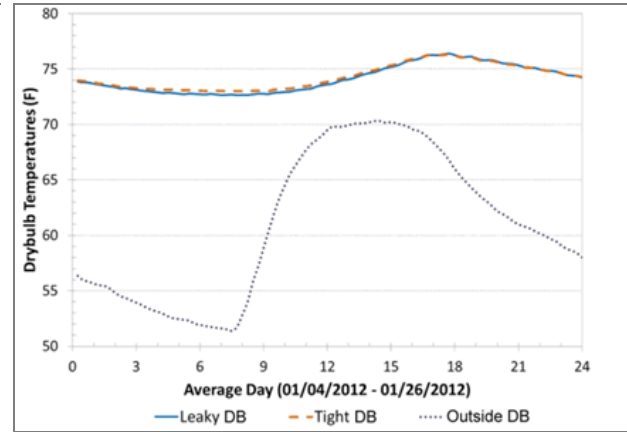


Figure 2. Average daily outdoor air dry bulb (Outside DB) and indoor air dry bulb temperatures for the leaky (leaky DB) and tight (Tight DB) homes during January 2012 test.

Heating was supplied by electric resistance strip heat in the air handler units. Over the test period, the heating energy uses were 119.1 kWh for the leaky home and 97.0 kWh for the tight home – a savings of 18.6%.

However, there were moisture concerns in the tight home. Figure 3 plots the outdoor and indoor dew point temperatures during the test period. Due to internal moisture generation, the dew point temperatures in the homes are higher than outdoors. Note that while the leaky home dew point is greater than outdoors, the tight home dew point is as much as 40 °F greater than outdoors during the coldest period. As shown in Figure 4, this resulted in excessive indoor relative humidity in the tight home, reaching values up to 80% and averaging about 20% greater than in the leaky home.

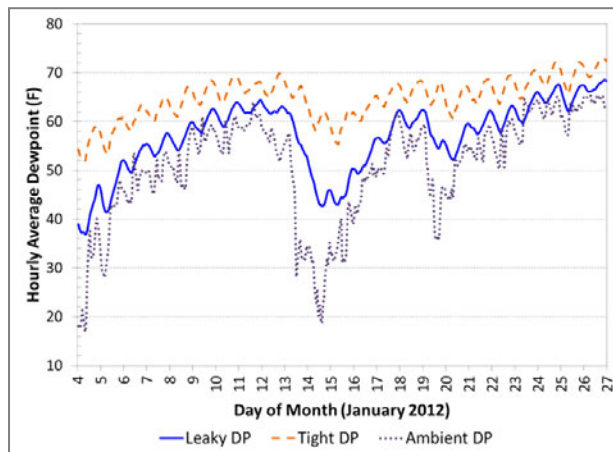


Figure 3. Dewpoint temperatures for outdoors (Ambient DP) and indoors for leaky (Leaky DP) and tight (Tight DP) homes during January 2012 tests.

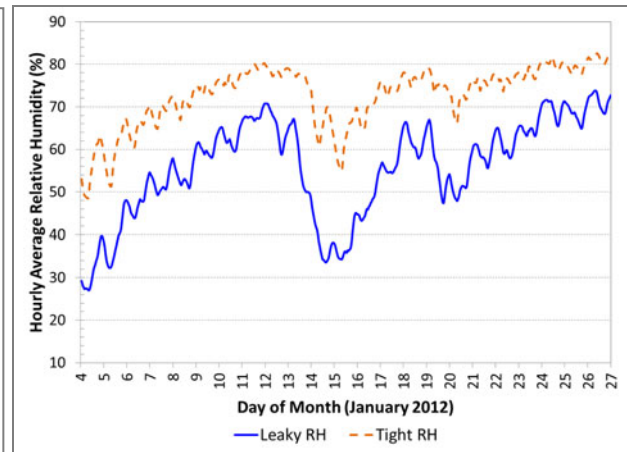


Figure 4. Indoor relative humidity for leaky (Leaky RH) and tight (Tight RH) homes during January 2012 tests.

This also resulted in significant hours when the indoor dewpoint temperature in the tight home was higher than the interior window temperature. The resulting condensation on the single-pane windows was significant during cold spells. Given that each 3.5 pounds of water condensing on the interior of windows represents an additional kWh lost to the outside through the glazing, this represents a previously unexplored heat loss mechanism for single glazed windows.

Forced ventilation. In mid-August 2012, an energy recovery ventilation system (Honeywell ER-200) was installed in the west (tight) home. The enthalpy recovery section of the unit was disabled so it operated as a supply-only ventilation system. The ventilation system was sized to comply with ASHRAE 62.2-2013 for a 3-bedroom home. The total ventilation requirement in accordance with this Standard is 73 cfm. The infiltration component of the ventilation was calculated in accordance with the Standard to be 10 cfm, with a resulting fan ventilation requirement of 63 cfm.

When in operation, the supply ventilation system provides the required $63 (\pm 3)$ cfm of outdoor air into the space. This was verified using a calibrated flow measurement. Measured power use of the ventilation system was $74 (\pm 2)$ Watts continuous (1.17 W/cfm) or 1.77 kWh/day. It should be noted that this value is excessive compared with ventilation fans in the current marketplace that can provide the same supply-only ventilation rate at 0.15-0.30 W/cfm. Following installation, the west home was alternated between continuous ventilation with the whole-house ventilation system and no mechanical ventilation to measure the differences in indoor conditions resulting from operation of the ventilation system.

Winter results with 2-week cycle of mechanical ventilation. For the winter of 2012–2013, the tight west building was mechanically ventilated on a two week cycle. The leaky east building remained without mechanical ventilation. Both buildings used a schedule of 11 lb/day of internal moisture generation. Window temperature measurements were also added for the second winter.

Figure 5 provides the measured infiltration rates during the period of these tests. The cold spells during this test period were not as pronounced as those during the 2011-2012 winter with low temperatures reaching only about 40 °F. For the leaky home the average air exchange rate over the test period was 0.304 ach and for the tight home with supply ventilation the average air exchange rate over the test period was 0.302 ach. For the tight home without mechanical ventilation the average air exchange rate over the test period was 0.063 ach. To estimate energy savings from one house to the next, only days with 1,000 Wh of heating were included to eliminate any significant measurement error during periods of low heating demand. Days of ventilation transition were also not included. This left 11 days of heating when the vent fan was turned off. The total heating used in the leaky unit those days was 70.2 kWh, and the tight unit used 70.4 kWh, showing no significant difference. This result is counter to the expected result and different than the result obtained in the first winter where the tight home saved 18.6% energy use during the previous winter measurement period.

There were 16 days when the homes were ventilated and heating equaled or exceeded 1,000 Wh. The measured heating energy use consistently shows greater heating use in the ventilated unit when the ventilation is on. The total heating used in the leaky unit those days was 95.6 kWh, and the tight ventilated unit used 110.2 kWh or 15.3% greater heating energy use in the tight ventilated home than the leaky home.

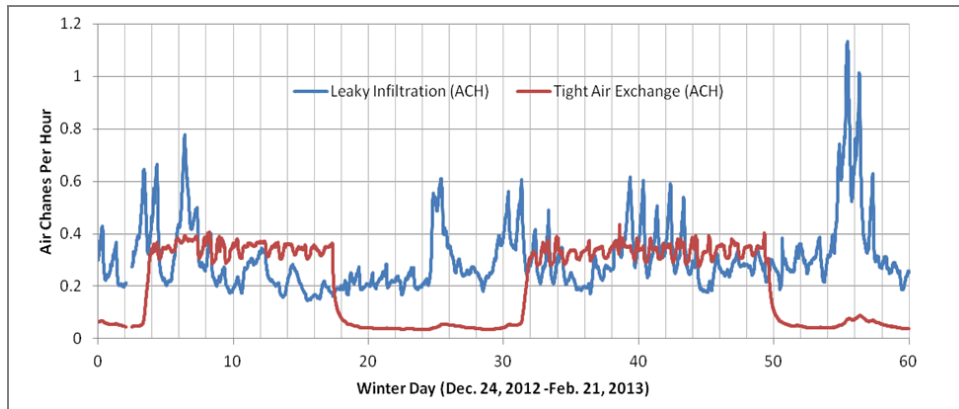


Figure 5. Air exchange rate for leaky (blue) and tight (red) homes during ventilation tests in winter 2012-2013. The red line shows impact on air exchange rate resulting from toggling the vent fan in the tight home between on and off positions (see also Figure 7).

As anticipated, window condensation was observed in the tight unit during times of non-venting but not in the leaky home. Figures 6 and 7 show an image of the window condensation and a plot of the relevant dew point and window temperatures on January 23, 2013. Note that the dew point temperatures in the tight home are about 10 °F greater than those in the leaky home and that they exceed both the top and bottom window temperatures during the evenings during this period.



Figure 6. Unvented tight house north-facing window condensation January 23, 2013.

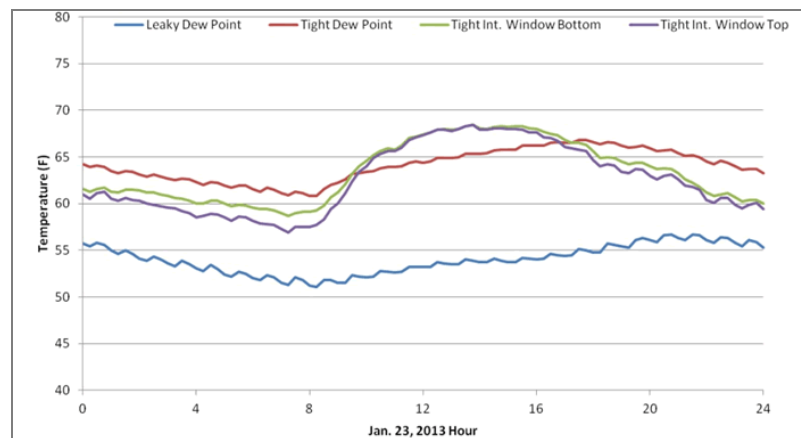


Figure 7. Dew point temperatures in the leaky (blue) and tight (red) homes and top unscreened (purple) and bottom screened (green) window temperatures in the tight home on January 23, 2013.

Summer Results

There is little empirical data from controlled experiments on how envelope air tightness and ventilation levels impact interior moisture levels in homes in hot, humid climates. The experiments reported here are designed to assess the indoor moisture control and cooling load impacts of airtightness and mechanical ventilation in homes in hot-humid climates. Over the summer of 2012, the west (tight) home was mechanically ventilated at a rate of 63 cfm using supply-only ventilation for alternating two-week periods. This is the same ventilation rate as used in the winter tests.

Comparative summer testing showed that the tight home exhibited little if any air conditioning (AC) energy savings and only modest indoor RH differences during periods when the mechanical ventilation system was turned off. However, when mechanical supply ventilation was used in the tight home, more significant differences between leaky and tight home energy use and indoor moisture levels resulted.

For mechanically ventilated periods, cooling energy use increased by 20-38% or about 4 kWh per day. Part of this increase resulted from the mechanical ventilation system fan itself, which added almost 1.8 kWh per day to the cooling load. Given the air conditioning equipment COP of about 3.5, the estimated cooling energy use increase is about 0.5 kWh per day. Use of current marketplace supply-only ventilation fans, with a power requirement of 0.25 W/cfm, would reduce the added fan heat cooling load substantially, resulting in an added cooling energy use of only 0.1 kWh instead of 0.5 kWh.

Compared with the leaky home, mechanical ventilation of the tight home increased indoor RH modestly by 2-5%. However, mechanical ventilation increased the comparative quantity of air conditioner moisture removal significantly by 27%. A complete set of results for these tests throughout the entire summer is reported in Parker et al. (2013).

Figures 8 and 9 show the average daily indoor and outdoor temperature and moisture conditions over a 10-day test period in October. Daily average indoor RH is 2.2% greater in the tight, mechanically ventilated home than in the leaky, unvented home.

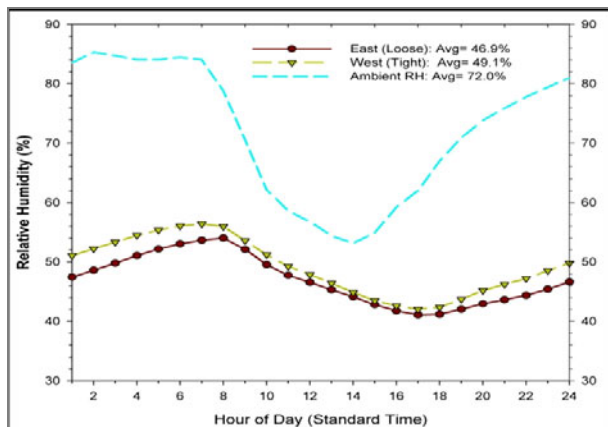


Figure 8. Daily average indoor and outdoor relative humidity during October 10-20, 2012 test period.

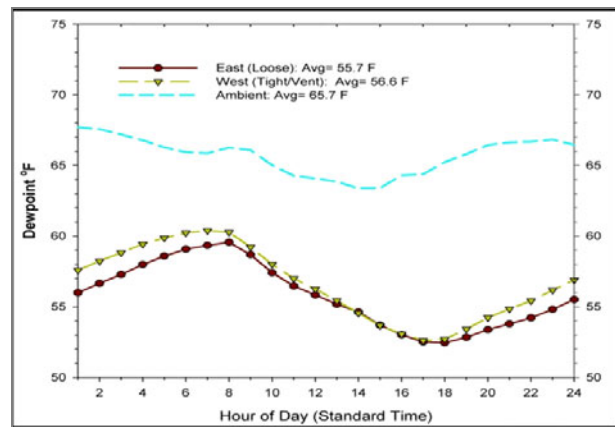


Figure 9. Daily average indoor and outdoor dew point temperature during October 10-20, 2012 test period.

Figure 10 shows average daily indoor and outdoor temperatures and cooling energy use for the two homes and Figure 11 shows the average daily air conditioner moisture removal (measured condensate) for the two homes.

While the daily average ambient average temperature over the 10 day period was 76.2 °F, the daily average high temperature was about 83 °F and, as shown in Figure 10, cooling energy was required in both homes. Measured daily average cooling energy use is 27% greater in the mechanically ventilated tight home and daily average moisture removal (air conditioner condensate) is 63% greater in the mechanically ventilated tight home. These preliminary empirical data indicate that in hot, humid climates, tight (2 ach50) homes ventilated to ASHRAE 62.2-2013 standards using supply ventilation will likely have greater indoor RH and greater air

conditioning energy use than their fairly leaky (8 ach50), unvented counterparts. At the same time, leaky, unvented homes may experience unacceptable build-up of indoor pollutants due to low levels of air exchange.

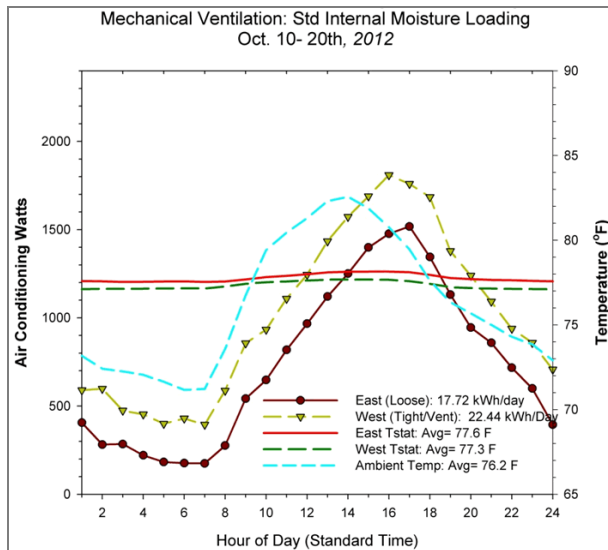


Figure 10. Average daily outdoor and indoor temperatures and cooling energy use for leaky and tight homes during October 10-20, 2012 test period.

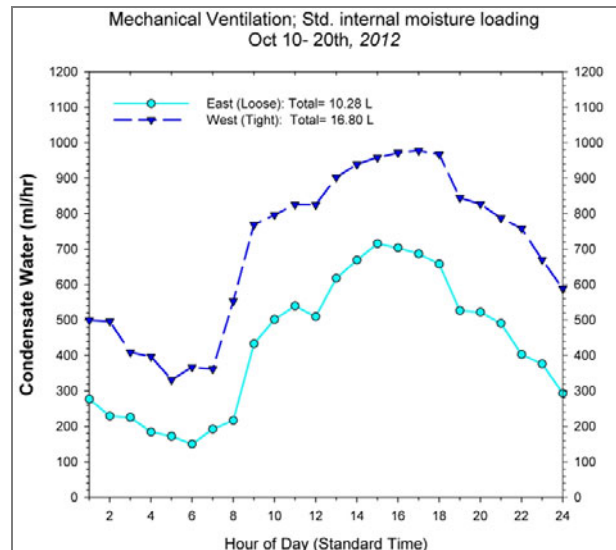


Figure 11. Average daily air conditioner moisture removal (condensate) for tight and leaky homes during October 10-20, 2012 test period.

It is also important to point out that supply ventilation systems, as used in these experiments, do not result in any building envelope moisture buffering that likely occur with exhaust ventilation systems. Additionally, exhaust ventilation systems do not result in the addition of fan energy to the conditioned space. Balanced ventilation systems, on the other hand, result in the addition of a fan heat load as well as the direct injection of ventilation air moisture into the conditioned space. Energy recovery ventilation systems greatly modify these impacts by exchanging both heat and moisture between the incoming and outgoing ventilation air streams.

Simulated Dehumidification and Energy Use

While no attempt has been made yet to validate simulation models against the measured data from the experiments, it is instructive to examine the sensitivity of energy use and indoor moisture levels as a function of home thermal efficiency and air tightness for a variety of climates and ventilation system types.

High-Performance New Homes

Methodology. A simulation modeling study examining the whole-house mechanical ventilation impacts in archetypical DOE Zero Energy Ready Home in twelve U.S. cities in five IECC climate zones was conducted for the U.S. DOE Building America program (Martin 2013). A total of 864 simulations were run for new home configurations using two building archetypes, two building leakage rates, two building orientations, three ventilation system types, three ventilation rates, and 12 climates.

The study was conducted using EnergyGauge® USA simulation software ¹ (Fuehrlein, et al. 2000). EnergyGauge uses an effective capacitance (EC) moisture adsorption and desorption model to account for moisture buffering in the indoor environment. The EC and EMPD (effective moisture penetration depth) moisture models have been recently compared against detailed heat and moisture transfer (HAMT) models in studies by NREL (Woods, Winkler, and Christensen 2013a). Woods, Winkler, and Christensen (2013b) concluded that “if hours above 60% RH is used as a metric, the EMPD and EC models generally produce similar results, except for high EC values ($EC > 30$).” An EC value of 10 is used by EnergyGauge USA in the simulations reported here. This EC value matches a value obtained through field studies by Cummings and Kamel (1988).

The hourly simulation results were post-processed to both calculate moisture removal quantities required to maintain indoor RH below prescribed levels and to segregate data into heating hours, cooling hours and floating hours (no heating or cooling required) to more explicitly define the seasonal energy and moisture impacts of ASHRAE 62.2-2013 in very high-performance home archetypes with HERS Index scores in the low to mid 50s. Table 1 provides the general geometric characteristics and the ASHRAE 62.2-2013 total air exchange rate (Q_{tot}) requirements of the two archetypes. Each archetype is configured to have two envelope leakage rates: tight with ach50 = 3.0 and very tight with ach50 = 1.5. The envelope, lighting, appliances and equipment efficiencies are specified to comply with the DOE Zero Energy Ready Home program (energy.gov 2013). Internal gains for the archetypes were set to 57.8 kBtu/day sensible and 12 lb/day latent (total of 70.4 kBtu/day).

Table 1. Geometric characteristics of simulation archetypes*

| Stories | Footprint | Nbr | Area | Height | Volume | N-S wins | E-W wins | Q_{tot} |
|---------|-----------|-----|----------------------|--------|------------------------|---------------------|---------------------|-----------|
| 1-story | 40' x 50' | 3 | 2000 ft ² | 9'-0" | 18,000 ft ³ | 210 ft ² | 90 ft ² | 90 cfm |
| 2-story | 30' x 40' | 3 | 2400 ft ² | 17'-6" | 21,000 ft ³ | 252 ft ² | 108 ft ² | 102 cfm |

* Where ‘Nbr’ is the number of bedrooms ‘N-S win’ is the area of windows facing north and south and ‘E-W win’ is the area of windows facing east and west and Q_{tot} is the total required ventilation air flow rate.

The twelve TMY3 weather sites used in the simulations along with their ASHRAE 62.2-2013 weather and shielding factors (wsf) are shown in Table 2.

Table 2. Climate locations for ventilation study simulations

| Climate Type | TMY3 City | wsf* |
|------------------|-----------------|------|
| Warm-Humid Zone | Orlando, FL | 0.39 |
| Warm-Humid Zone | Houston, TX | 0.40 |
| Warm-Humid Zone | Charleston, SC | 0.43 |
| Mixed-Humid Zone | Baltimore, MD | 0.50 |
| Mixed-Humid Zone | Kansas City, MO | 0.60 |
| Mixed-Humid Zone | Charlotte, NC | 0.43 |
| Cold-Humid Zone | Minneapolis, MN | 0.63 |

¹ EnergyGauge USA is a RESNET-accredited software tool based on a DOE-2.1E simulation engine that has been substantially modified using functions that simulate additional building features that are not included in DOE-2.1E “out of the box.”

| Climate Type | TMY3 City | wsf* |
|-----------------|-----------------|------|
| Cold-Humid Zone | Chicago, IL | 0.60 |
| Dry Zone | Phoenix, AZ | 0.43 |
| Dry Zone | Denver, CO | 0.61 |
| Marine Zone | Los Angeles, CA | 0.42 |
| Marine Zone | Seattle, WA | 0.56 |

* Weather and shielding factor from ASHRAE 62.2-2013

Whole-house mechanical ventilation systems. Three different mechanical ventilation system types were simulated: 1) exhaust-only [EXH], 2) energy recovery ventilator [ERV], and 3) central fan integrated [FanC]. Equation 4.6 of ASHRAE 62.2-2013 was used to determine ventilation fan flow requirements, as follows:

$$Q_{fan} = Q_{tot} - Q_{inf}$$

where

$$Q_{tot} = 0.03 * CFA + 7.5 * (Nbr + 1) \text{ [see Table 1]}$$

The provisions of 62.2 were also used to determine the expected natural infiltration rate (Q_{inf}). This calculation results in a different Q_{inf} for each archetype (due to difference in height) for each envelope tightness and in each climate (due to differences in wsf). It is also important to note that Q_{fan} is calculated as the simple difference between Q_{tot} and Q_{inf} while simulation specifications for both performance-based code compliance (IECC 2012) and home energy ratings (ANSI/RESNET 2014) require that infiltration and mechanical ventilation fan flows be added in quadrature, as follows:

$$Q = Q_{bal} + (Q_{unbal}^2 + Q_{inf}^2)^{0.5}$$

As a result, unbalanced whole-house mechanical ventilation systems result in slightly lower simulated air exchange flow rates than balanced systems.

Ventilation fan power requirements were varied by ventilation system type. For the exhaust-only systems (EXH), fans were sized at 0.30 watts/cfm; for the energy recovery ventilation systems (ERV), fan power was 1.0 watts/cfm; and for the central fan integrated systems (FanC), the fan was sized at 0.375 watts/cfm. Fan power for the FanC system was only accumulated during periods of time when heating and cooling were not required but the ventilation fan was required to meet 62.2 ventilation requirements.

Results. Of interest are the total air exchange rates (infiltration + ventilation) resulting from the simulations. Given the fact that mechanical ventilation is calculated by simple subtraction of the estimated infiltration rate from the total ventilation requirement and the quadrature assumptions of the simulation model, how does the simulated annual average total air exchange rate vary? Figure 12 shows the total air exchange rate results for the tight, 3 ach50 homes and Figure 13 shows the same results for the very tight, 1.5 ach50 homes.

These results illustrate a couple of findings. First, total annual air exchange rates are not excessive with maximum total air exchange rates generally less than 0.30 air exchanges per hour, regardless of climate, home type or ventilation system type. Second, the results illustrate the fact that total air exchange rates for unbalanced ventilation system will approach that of balanced

systems as homes become tighter because as infiltration approaches zero, the impacts of quadrature on the total diminish. While the difference between average total air exchange rate for the balanced and unbalanced ventilation systems in the 3 ach50 homes is about 24%, it is reduced to about 10% in the 1.5 ach50 homes.

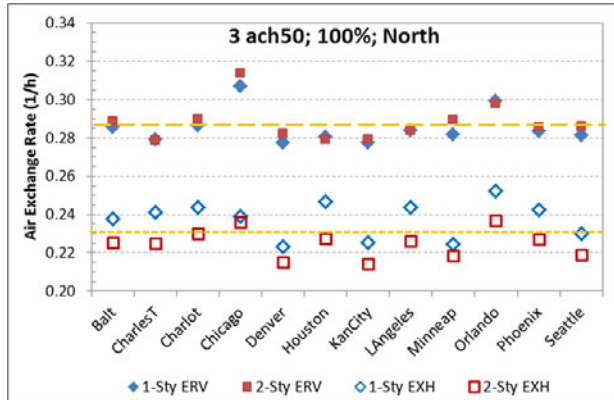


Figure 12. Air exchange rate for 3 ach50 homes. Balanced avg. = 0.287 ach and unbalanced avg. = 0.231 ach.

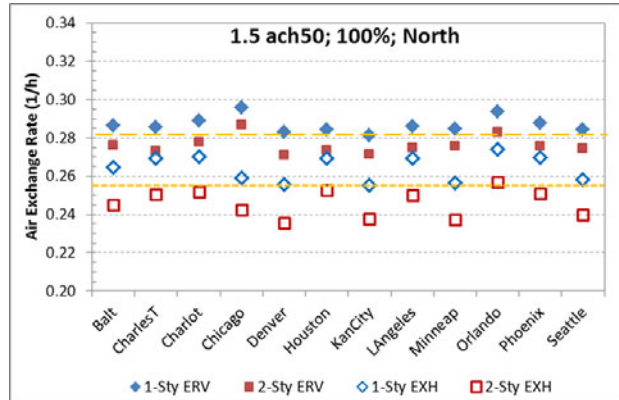


Figure 13. Air exchange rates for 1.5 ach50 homes. Balanced avg. = 0.281 ach and unbalanced avg. = 0.255 ach.

Also of significant interest is how mechanical ventilation system type impacts resulting indoor RH conditions in hot, humid climates. Figures 14 and 15 show summary information for all cities included in the study. These figures clearly show the climates of concern, where annual hours above 60% RH can exceed 1500 hours. The fact that Los Angeles is one of these cities is surprising to many but it becomes clear from Figure 15 that this occurs almost entirely because it is a mild, moist climate. Note that unlike Charleston, Houston and Orlando, Los Angeles has very few cooling hours where the RH is greater than 60% - almost all of its hours greater than 60% are floating hours when neither heating or cooling is required.

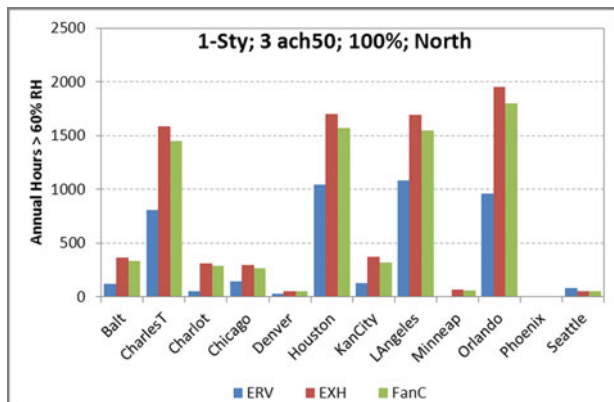


Figure 14. Annual hours >60% RH for 3 vent types.

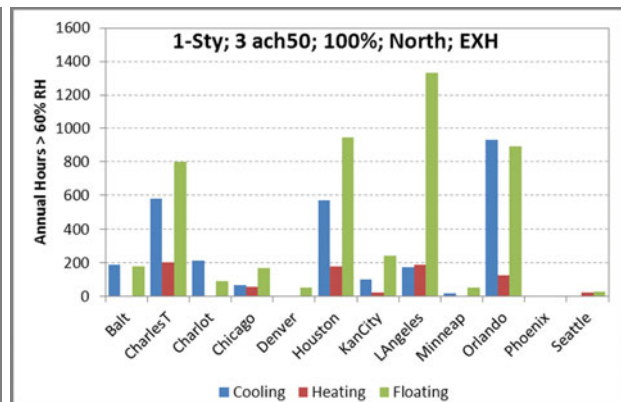


Figure 15. Annual hours >60% RH for 3 load conditions.

It is also interesting to note in Figure 14 that the supply-only central fan integrated system (FanC) shows slightly less hours above 60% RH than the exhaust-only system. This occurs because the simulation tool adds the fan heat from the supply-only system (FanC) to the indoor air while it exhausts the fan heat from the exhaust-only system to the outdoors. This results in slightly longer air conditioner run times for the FanC system than for the EXH system.

The question as to how much ASHRAE 62.2-2013 continuous ventilation rates might increase indoor relative humidity in humid climates is also of considerable interest to the building community. However, this question is also related to the issue of what level of indoor RH should be used as the metric of concern. To examine these questions, Figures 16 and 17 are presented.

Figure 16 shows clearly that if 65% RH is the critical level, the city of Los Angeles is no longer a candidate for concern. While Los Angeles shows many hours greater than 60% RH, it shows almost none greater than 65%. On the other hand, Charleston, Houston and Orlando show 500 or more hours where indoor humidity is likely to exceed 65%. Figure 17 shows similar findings. While the mean indoor RH is increased by ventilation and the number of hours >60% is increased, the number of hours greater than 65% RH remains almost unaffected.

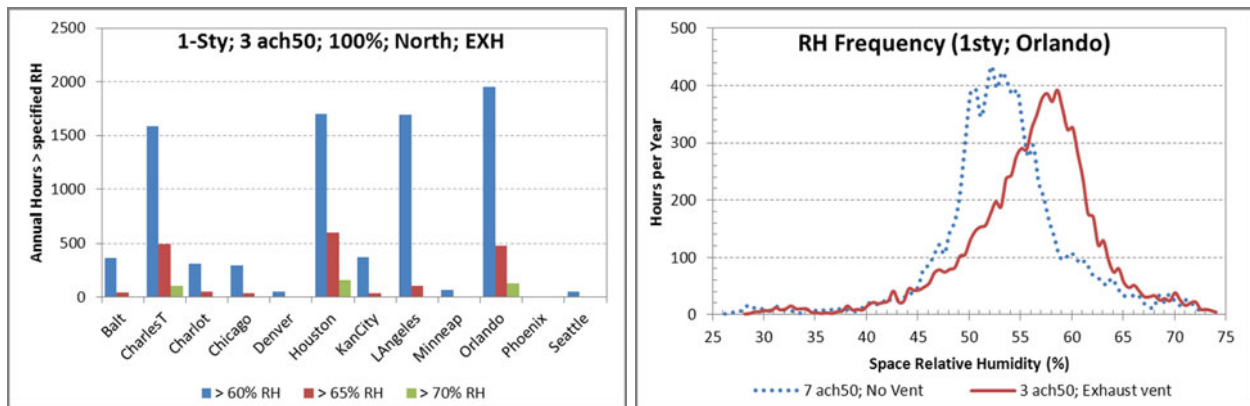


Figure 16. Hours > than 3 specified indoor RH levels.

Figure 17. Unvented and vented of indoor RH levels.

To maintain indoor RH below 60% requires some dehumidification in all but dry climates and considerable dehumidification (800-1,000 lb/y) in some climates. To determine dehumidification loads, a dehumidifier EF (energy factor) of 1.47 L/kWh was assumed. Recent field data indicates that conventional dehumidifiers operate closer to 0.8 L/kWh (Mattison and Korn 2012), which would tend to double energy use and cost. However, dehumidifiers with EF greater than 1.47 L/kWh are available in the market and this study concentrates on high-performance homes and assumes best technology. Figure 18 shows the quantity of moisture that must be removed for the two home leakages using exhaust-only ventilation systems and Figure 19 shows total annual estimated operating costs for the three ventilation system types in the 1-story, 3 ach50 homes.

In Figure 18, the fact that total air exchange rate for unbalanced ventilation systems is increased as the home becomes tighter (see earlier discussion and Figures 12 and 13) is evident in the required moisture removal results. The 1.5 ach50 home requires approximately 20% more moisture removal than the 3 ach50 homes in all four of the climates that experience a significant number of hours greater than 60% RH (excepting Los Angeles).

In order to make the annual energy cost comparison free of local energy cost dependencies, the energy costs used to derive annual operating cost are held at \$0.12/kWh and \$1.08/therm for all cities. Figure 19 illustrates that annual operating cost are principally a matter of climate severity. Ventilation system type makes only a small relative differences in operating costs as compared with the climate impacts. As expected, the largest operating costs occur in the coldest climates and the lowest costs occur in the more benign climates. Conventional

dehumidifiers often have much lower EF than assumed for this study. However, the added cost of the less efficient technology (EF = 0.80) is only about \$30 in Orlando (the worst case city in this analysis).

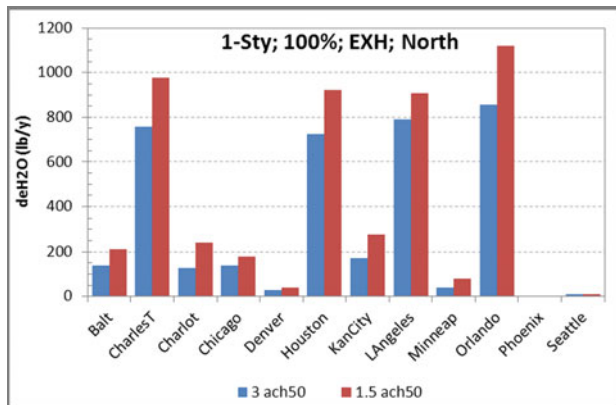


Figure 18. Required dehumidification for RH ≤ 60%.

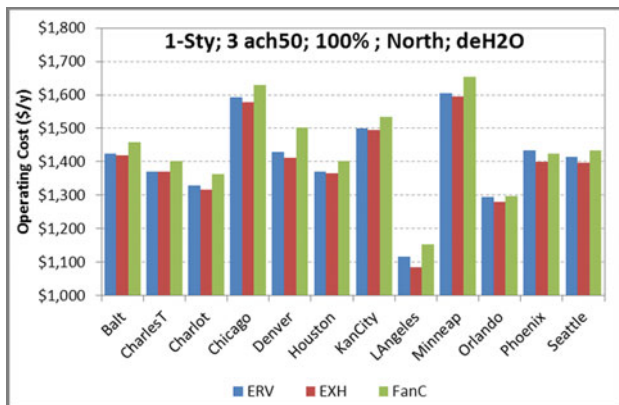


Figure 19. Annual operating costs for 3 vent systems.

Existing Home Retrofits

To evaluate the simulated impacts of existing home retrofits where air sealing is employed, a second set of simulations using the 1-story archetype in Orlando, Florida was conducted. For these simulations, the envelope and equipment features of the home were modified to be minimally compliant with the 2000 IECC. The existing home was assumed to have envelope leakage of 11 ach50 and be retrofitted through air sealing to achieve 5 ach50. Retrofit field studies in Florida indicate that existing home leakage of 11 ach50 is typical (McIlvaine, Sutherland and Martin 2013).

Results. The simulated annual average total air exchange rate for the existing home is 91.1cfm (0.304 ach), slightly greater than the ASHRAE 62.2 total ventilation requirement of 90 cfm. Indoor RH results for the existing home without mechanical ventilation or dehumidification are shown in Figure 20. While the average annual air exchange rate for the existing home is slightly greater than those of the high-performance home with mechanical ventilation, its number of hours greater than 60% RH is significantly less (369 for the existing home versus 1,950 for EXH and 959 for ERV mechanical ventilation in the comparable high-performance homes). Comparing the hourly RH results for the existing home with those in Figure 16 indicates that the existing home behaves much more like the ERV home than the EXH home. Two influences are at work. First, the envelope sensible gains are significantly greater than in the high performance homes, causing the sensible cooling load to be significantly larger and resulting in much greater air conditioning runtime. Second, in summer when outdoor dew point temperatures

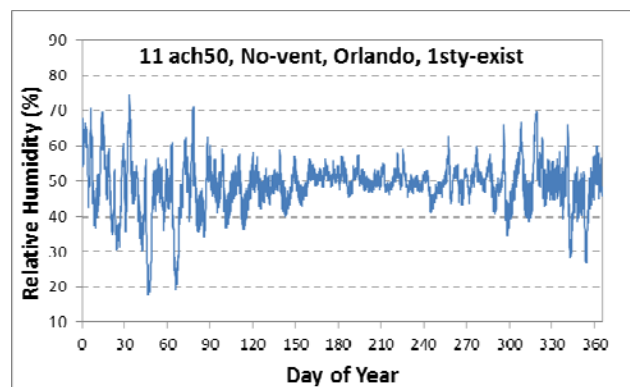


Figure 20. Hourly RH results for Orlando existing home.

are their greatest, wind speeds and temperature differences (driving forces) and natural infiltration is are their lowest and air conditioning loads are their largest, providing greater dehumidification.

When the existing home is retrofitted to 5 ach50, it requires mechanical ventilation to achieve ASHRAE 62.2 standards. A series of options for achieving the required ventilation rates is analyzed to compare relative energy savings and costs. Mechanical ventilation systems of both standard fan efficiency and best available fan efficiency are simulated. Two ERV effectivenesses are also simulated – one at 40% effective (standard) and one at 60% effective (ENERGY STAR). Table 3 presents the results of these simulations.

Table 3. Ventilation energy performance and cost options for existing home retrofit

| ach50 | Dehum %RH | Vent Type | Sup/Exh Fan cfm | Fan Watts | Cooling kWh/y | Heating kWh/y | Fan kWh/y | Dehum kWh/y | Dehum Cost/y | Total Opn Cost/y | Cost delta |
|-------|-----------|-------------|-----------------|-----------|---------------|---------------|-----------|-------------|--------------|------------------|------------|
| 11 | None | None | 0/0 | 0 | 5546 | 319 | 0 | 0 | \$0.00 | \$1,935 | base |
| 11 | 60% | None | 0/0 | 0 | 5593 | 310 | 0 | 152 | \$18.24 | \$1,958 | \$23 |
| 5 | None** | None | 0/0 | 0 | 5156 | 196 | 0 | 0 | \$0.00 | \$1,874 | -\$62 |
| 5 | 60% | Supply-only | 63/0 | 19 | 5586 | 233 | 166 | 95 | \$11.40 | \$1,961 | \$26 |
| 5 | 60% | Supply-only | 63/0 | 9.5 | 5566 | 234 | 84 | 96 | \$11.52 | \$1,949 | \$14 |
| 5 | 60% | ERV (40%) | 63/57 | 60 | 5584 | 242 | 526 | 97 | \$11.64 | \$2,005 | \$70 |
| 5 | 60% | ERV (40%) | 63/57 | 30 | 5551 | 245 | 263 | 99 | \$11.88 | \$1,971 | \$35 |
| 5 | 60% | ERV (60%) | 63/57 | 60 | 5475 | 224 | 526 | 77 | \$9.24 | \$1,988 | \$52 |
| 5 | 60% | ERV (60%) | 63/57 | 30 | 5442 | 226 | 263 | 78 | \$9.36 | \$1,953 | \$17 |

It is important to note that the simulation for 5 ach50 and no mechanical ventilation does not comply with ASHRAE 62.2 and is not recommended. The table shows that annual operating costs for the existing home are significantly greater than those of the corresponding high-performance homes shown in Figure 22 (~\$2,000 versus ~\$1,300). Table 3 also shows that the cost premium for maintaining indoor RH below 60% at all times of the year is variable but small (\$14 - \$70 per year). This is also dependent on the dehumidification efficiency, which for the most common market products (EF = 0.80 L/kWh) could double the dehumidification costs shown here (\$9 - \$18 per year).

Conclusions

The experimental results indicate that very tight construction in humid climates (2 ach50) will risk excessive (and potentially damaging) indoor moisture levels in winter if ventilation of some type is not employed. For the loose experimental home (8 ach50), no evidence of damaging humidity was observed. However, the fact that building tightness level cannot be readily anticipated argues for ventilation in new homes appropriate to ASHRAE 62-2.

In summer, the experimental results indicate that indoor humidity levels will be greater in tight homes that are mechanically ventilated using supply-only ventilation systems to achieve ASHRAE 62.2 standards than in loose, unventilated homes. However, simulations suggest that

use of energy recovery ventilator (ERV) systems may significantly reduce indoor humidity levels in such homes. The experiments to confirm this have not yet been conducted.

The experimental results also indicate that loose homes (~8 ach50) may not achieve ASHRAE 62.2-2013 standards for total air exchange in hot humid climates due to the lack of driving forces. Results also show that standard air conditioners will remove significant quantities of moisture vapor from the indoor air, greatly ameliorating summer RH concerns in homes complying with ASHRAE 62.2-2013.

Modeling results of high-performance homes show similar trends, with a significant number of hours where predicted indoor RH exceeds 60% in humid climates. Results also show that the majority of these hours occur during periods when air conditioning is not required (floating hours), especially where ERV systems are employed. Modeling results also show that if the critical level is raised from 60% RH to 65% RH, a large fraction of the hours of concern are removed.

Modeling results of existing homes in central Florida with envelope leakage of 11 ach50, suggest that the energy use for mechanical ventilation and dehumidification overcomes the potential heating and cooling energy savings that might otherwise be expected from retrofit air tightening to 5 ach50. And modeling results for both new and existing homes suggest that the operating cost of homes is only modestly impacted by the type of ventilation system selected and the operating cost of dehumidification.

A key gap and area of ongoing research is the cost-effective application of ventilation with systems and approaches that reduce energy consumption, improve humidity control, and improve indoor air quality. Applications not currently considered by ASHRAE 62.2 that should be considered for further research include:

- Managing indoor air pollutants in ways other than outdoor air exchange
- Quantifying exposure to pollutants, and mitigation of that exposure, over a time scale shorter than the annual average
- Accounting for the quality of the outdoor air for different outdoor environs and ventilation and filtration systems types
- Accounting for ventilation air distribution effectiveness
- Application of demand- based ventilation systems.

Models that can accurately simulate the performance of advanced ventilation control systems in high performance buildings, along with associated humidity control systems in humid climates, are needed to provide best prospects for understand a wide range of scenarios related to the economics and operational success of high-performance homes. Intelligent controls that consider indoor and outdoor temperature and humidity conditions and prevailing weather conditions will likely lead to best system performance, both for saving energy, managing humidity and providing best indoor air quality. These should be fully researched.

Accurate simulation of ventilation and space conditioning control systems that operate on sub-hourly time scales coupled with the interacting heat and mass transfer effects is complex. Accurate and meaningful results depend on many poorly understood and documented phenomena, such as:

- Internal moisture generation rates

- Other moisture loads, including effects of construction moisture and rain wetting under solar loading
- Building moisture capacitance and the impacts of building material moisture adsorption/desorption
- Detailed space conditioning equipment, energy recovery ventilator and dehumidifier performance maps.

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