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A Review of Home Airtightness and Ventilation Approaches for Florida Building Commission Research

FSEC-CR-1977-14

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1. EXECUTIVE SUMMARY

This report presents a literature review, examination of experimental data, and calculations of energy impacts of using or not using various types of ventilation systems and presents alternative approaches to achieving acceptable levels of ventilation while avoiding the risks associated with tight home enclosures and potential mechanical system failures.

This work is a follow-up to a 1995 FSEC report to the Florida Department of Community Affairs that assessed the then-current infiltration practices of the Florida Energy Code (Cummings and Moyer 1995). Finding that Florida homes had become progressively more airtight, the report concluded:

> *…we can say with confidence that nearly all new Florida homes receive less ventilation air by means of natural infiltration than is called for by the ASHRAE 62-1989 ventilation standard (it calls for 0.35 ach or more).* ***Therefore, this report concludes that Florida houses should not be made tighter.*** *Blower door test data shows that Florida houses have become three times more airtight over the past 40 years, and that the majority of this airtightening occurred before the current infiltration practices came into effect in 1986.*

The 1995 report also stated that further tightening might necessitate mechanical ventilation systems to achieve acceptable indoor air quality and contained recommendations that the Florida Building Code should be modified to make homes more airtight between indoors and the attic, garage, and crawlspace, but less airtight at locations in the house envelope where the entering air would be of higher quality.

As the Florida Building Code adopts new airtightness and mechanical ventilation requirements, new equipment and control technologies become available and the future likely holds homes continuing to become more efficient, it is important to revisit these topics.

Research performed for this project found there is wide consensus that both controlling infiltration and providing mechanical ventilation is necessary for homes, but determining appropriate levels for each is much more involved. Considerations must include energy use, indoor humidity impacts and combustion safety.

Based on the totality of the research done for this project, the authors' position is to encourage "reasonably tight" Florida homes with neutral or slightly positive pressure mechanical ventilation. Specific recommendations include:

- Do not require further airtightening beyond the 2012 IECC requirement for homes to have an air leakage rate not exceeding 5 ACH50 in Florida.

- Consistent with the 1995 recommendations, focus on airtightness between indoors and the attic, garage, and crawlspace instead of locations in the house envelope where the entering air would be of higher quality.

- The amount of airflow required in ventilation standards has limited health-related validation. A health metric needs to be incorporated into ventilation standards and to do that, building scientists and medical researchers will need to collaborate. Although such research will take a long time, it should be conducted as there are health consequences in the balance.

- To minimize risk of health consequences source control should be advised more regularly than present. The means of doing so is beyond the scope of this study, but the public needs better education of the risk of pollutant sources in homes. Furthermore, residents need education on storing certain materials and chemicals outside the home.

- Ventilation systems should be designed to have the following features:
    - Flexible airflow rate. As standards change and more health-related research is conducted, the recommended flow rates may change. Furthermore, a system with adjustable rates will allow for field or seasonal adjustments.
    - Highly efficient fans. The ventilation system will use power and there is a fair amount of variation in energy use of fans. Oversized fans that run on slow speed may meet the needs for flexibility while saving energy as the power curve of motors usually results in reduced Watts per cfm. Energy use for whole house mechanical fans of less than 0.2 or 0.3 Watts per cfm may be able to be specified in codes in the near future.
    - Be positively pressured or balanced systems. Positively pressured and balanced systems provide control of where the air entering the home is coming from and reduce risks of mold and mildew on surfaces.
    - Be installed with air intakes at proper locations. The 2014 Florida Energy Conservation Code Section R403.5.2 requirement not allowing ventilation air to come from "attics, crawlspaces, attached enclosed garages or outdoor spaces adjacent to swimming pools or spas" should be added to the IECC. Furthermore the intake should not be near insecticide spray locations, car exhaust, air conditioning condensers or dryer exhausts.
    - Have a means to remove humidity of the ventilation air. Another research project is currently exploring options (Withers and Sonne 2014).

- Recommended systems include an enthalpy recovery ventilation (ERV) system. Moisture of entering air can be reduced with these systems. The systems use balanced airflow which requires two fans so they tend to use more energy than supply or exhaust only systems. ERVs are popular in the national marketplace and can be set up to meet most of the requirements listed above. In addition to the energy use and first cost, key concerns of such systems are the maintenance of two fans and the enthalpy exchange media.

- Supply only systems can be combined with dedicated outdoor air systems, the standard home air conditioner, and/or dehumidifiers to remove moisture and can be purchased and installed at a low first cost (albeit, the dehumidification solution may become expensive). A popular method in high efficient homes has been runtime supply ventilation systems that run only when the AC is on. They do an excellent job of bringing in air and keeping humidity under control when the AC runs frequently. However, they may also need to cycle on during other times which may include days when outside air is damp but not hot so the air conditioner thermostat does not call for cooling or dehumidification; at these times they may bring in air that will raise the humidity in the home. (For example, a late season tropical storm in November.)

- Failure rates of systems in limited field studies raise concerns about the longevity and home resident operation and maintenance of whole-house ventilation systems. If residents think they are obtaining outside air but do not know the system has failed that could be a health concern. Consideration should be given to mandating some type of alarm if there is a detected failure (much like home fire alarms).

- A research project should be initiated to study the effectiveness and failure rates of whole-house mechanical ventilation systems installed in Florida over the last 15 years.

2. INTRODUCTION

In the 1990's concerns were raised that homes were becoming increasingly airtight and that this airtightness might lead to indoor air, humidity control, and combustion safety problems. In 1995, a report was prepared by FSEC for the Florida Department of Community Affairs on the topic of building airtightness, titled "Reassessment of Airtightness Practices in the Florida Energy Code" (Cummings and Moyer 1995).

- The report indicated that Florida homes had become progressively more airtight, with home air leakage declining from about 22 ACH50 (air changes per hour at 50 pascals of pressure; a blower door test result) in the 1950's to about 4 or 5 ACH50 in 1995. The report found that residential construction had reached a point where added tightening could result in natural ventilation sufficiently small as to fall substantially short of levels needed for healthy indoor air quality.
- The report also stated that further tightening might well necessitate installation (and of course maintenance) of mechanical ventilation systems to achieve acceptable indoor air quality. It contained recommendations that the Florida Building Code should be modified to make homes more airtight between indoors and the attic, garage, and crawlspace, but less airtight at locations in the home envelope where the entering air would be of higher quality.

Since that 1995 report, residential construction codes have been modified as reflected in Section R402.4.1.2 of the 2012 IECC, which requires that a "building or dwelling unit shall be tested and verified as having an air leakage rate not exceeding 5 air changes per hour in Climate Zones 1 and 2…", which would cover all of Florida (IECC 2012). Additionally, building practices have continued to change over time and a number of groups and programs have also begun pushing to simultaneously make homes much tighter and to require mechanical ventilation. The saying "Build tight, ventilate right" represents a strongly held view among many within the buildings community. While this concept is appealing, there can be significant problems with making the house envelope very tight. Underlying this issue is the concern that when the house envelope is made very tight and mechanical ventilation systems are essential to achieving desired ventilation levels, the question arises, "Who will maintain the ventilation system and what happens to indoor air quality when the system fails or is turned off?"

One problem is that a tight house envelope creates the necessity of mechanical ventilation. The corollary to this is that when the mechanical system fails, is turned off, or diminishes in performance (such as a dirty filter or a slipping belt), the occupants of the tight home will likely suffer from poor indoor air quality. Field observations have repeatedly found that mechanical ventilation systems fail at alarmingly high rates due to motor burnout, dirty filters, slipping belts, and systems being turned off. In addition to a shortfall in outside air, failure of the mechanical system can lead to moisture problems such as elevated indoor relative humidity and mold growth during cold weather (Vieira et al. 2013).

A second problem relates to combustion safety. When a house is very tight, various forms of unbalanced air flow (such as exhaust fans without make-up air, unbalanced return air, and/or duct leakage) can lead to excessive depressurization of the indoor space which can lead to spillage or back-drafting of vented combustion devices (hot water heaters, furnaces, boilers, and fireplaces) (CMHC 1999). This can introduce combustion gases, including carbon monoxide, into the home and create a significant health risk. Negative pressure can also produce flame roll-out and the potential for a house fire.

A third problem relates to humidity in homes, which is a special concern because of the Florida climate.

- The most widely encouraged and employed method for providing mechanical ventilation in homes across the United States is continuous exhaust. Throughout much of the United States, exhaust ventilation does not create major problems. But this approach is generally questionable in Florida because it creates negative pressure. Combined with other factors beyond the control of the building code, such as homeowner thermostat set point and impermeable interior wall coverings, negative pressure has been found to cause mold growth in Florida homes and buildings (Moyer et al. 2001).

- Alternative methods of providing mechanical ventilation can produce positive pressure in homes. These systems involve a supply fan and duct, a balanced system or possible additional cooling systems. As such they are generally more complicated and more expensive than a simple exhaust system.

3. TASK 1

Task 1 involves a literature review, examination of experimental data, and calculations of energy impacts of using or not using various types of ventilation systems.

Over 40 articles, research reports, presentations and code documents were reviewed. Information sources included the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Building Science Corporation (BSC), Florida Solar Energy Center (FSEC), International Code Council (ICC), Lawrence Berkeley National Laboratory (LBNL) and the US Environmental Protection Agency (EPA).

One thing that is clear from the research is that this is not a simple, straightforward undertaking. A 2012 LBNL publication (Sherman and Walker 2012) summarizes the current state of affairs:

> *The ongoing challenge with airtightness is balancing the need to make buildings tighter to save energy and for improved comfort, with the need to provide sufficient air flow to maintain indoor air quality and avoid other issues such as natural draft combustion appliance backdrafting. Where this balance is to be struck is an ongoing topic of debate in the US.*

3.1 Measured Airtightness Data

As documented in the 1995 FSEC study, even at that time new Florida home construction was rather airtight. How tightness of that era compares to the tightness of homes built prior to 1995 is not known as few Florida house were tested for airtightness prior to 1990. Some studies have tested old and new homes and found the older homes as currently tested to be leakier than newer homes:

- A 2012 FSEC Code study (Withers et. al. 2012) found a sample of 31 Florida homes built to the 2009 Florida Energy Code to have an average ACH50 of 5.6 compared to a sample of 47 homes built to the 1984 Florida Energy Code which had an average ACH50 of 9.1 (all homes were tested in 2011 - 2012 so some or all of the difference may be due to failures over time of the older homes).

- Recent FSEC analysis of data from mainly central and some south Florida homes showed an average ACH50 rate of 9.7 for a sample of 13 homes built between 1975 and 1984 compared with 7.5 for 16 homes built between 1985 and 1994, and 5.9 for a sample of 16 homes built between 1995 and 2006
- A 2003 FSEC study (Cummings 2003) found a sample of 11 central Florida homes built in 2001 to have an average ACH50 of 5.7.

3.2 Airtightness and Whole House Ventilation Requirement Trends

Different standards for air tightness exist in the residential marketplace. Home airtightness requirements ranging from the 2012 International Energy Conservation Code (IECC) level of 5 ACH50 to Passive House's 0.6 ACH50 were found. As noted in the introduction, "Build it tight, ventilate it right" is advocated in a number of publications with some looking at energy savings and other considerations for specific airtightness levels.

In general, there is a definite trend toward tighter homes:

- While the 2009 IECC provides two airtightness options, either a visual inspection using a provided checklist or tested ACH50 < 7, the 2012 IECC requires both a visual inspection and a tested ACH50 <= 5 in Climate Zones 1 and 2, which includes all of Florida (IECC 2009 and 2012).

- The US Environmental Protection Agency's ENERGY STAR Homes program version 3 prescriptive path requirement for Florida is an ACH50 <= 7 while the new version 3.1 Florida prescriptive requirement is an ACH50 <= 5 (EPA 2014).

- The US Department of Energy's Zero Energy Ready Home (formerly Challenge Home) program which starts with ENERGY STAR qualification as a baseline, requires an ACH50 of <= 3 for prescriptive compliance in Climate Zones 1 and 2 (US DOE 2014).

Even tighter requirements are found in the 2012 edition of Canada's R-2000 Standard (NRC 2014) which stipulates an ACH50 of <= 1.5 and, as noted above, in the Passive House criteria (Passive House Alliance 2014) which stipulates a maximum air leakage equivalent to 0.6 ACH50.

There are also a number of residential mechanical ventilation rate requirements. Four of the commonly referenced requirements are:

- ASHRAE Standard 62.2-2010: Continuous ventilation Rate (cfm) = (CFA * 0.01) + (7.5*Nbr+1), where CFA is the conditioned floor area in square feet and N_{br} is the number of bedrooms. The 2010 Standard assumes infiltration at 2 cfm per 100 square feet of conditioned area. There is also an intermittent option.

- ASHRAE Standard 62.2-2013: Continuous ventilation Rate (cfm) = (CFA * 0.03) + (7.5*Nbr+1), where CFA is the conditioned floor area in square feet and N_{br} is the number of bedrooms. For the 2013 Standard, no infiltration is assumed, but ventilation "credit" can be taken for calculated infiltration that is based on blower door measurements. There is also an intermittent option.

- 2012 IMC: Outside of an exception for engineered ventilation systems provided by registered design professionals, ventilation is required for any home that has less than 5 ACH50 in the 2012 International Mechanical Code. The IMC sets the continuous ventilation at 0.35 ach (air changes per hour) but not less than 15 cfm/person, where the number of persons equals the number of bedrooms plus 1.
- 2012 IRC: The 2012 International Residential Code sets continuous ventilation at a rate provided by Table M1507.3.3(1). It also has an intermittent option via multiplier factors provided in Table M1507.3.3(2).

The new 2014 Florida Mechanical Code will also require that mechanical ventilation be provided for any home that has less than 5 ACH50. The Code will use the same language as Chapter 4 of the International Mechanical Code (IMC 2012), which states that mechanical ventilation must be provided by "a method of supply air and return or *exhaust air.*" It also requires that the amount of supply air be approximately equal to the amount of return and exhaust air. The IMC-required continuous ventilation rate for private dwellings or IRC Table M1507.3.3(1) rate will be required by Florida as well.

The new Florida 5th Edition (2014) Energy Conservation Code will follow the 2012 IECC requirement that newly constructed houses be tested for envelope air leakage, not permitting leakage in excess of 5 ACH50 , which means that most new homes will require mechanical ventilation in order to comply with the combination of the energy and mechanical portions of the Code. Additions to the 2012 IECC were made in the Florida 5th Edition (2014) Energy Conservation Code to limit maximum mechanical ventilation to ASHRAE 62-2 levels, prevent ventilation air being supplied form attics, crawlspaces, garages, or swimming pool areas, and if air is drawn from an enclosed space, the space be insulated [Section 403.5.2].

Due to Florida's relatively small infiltration driving forces (most notably the lack of a significant stack effect), typical annual average total air exchange rates have been about 0.20 ach or less. Even so, historically Florida has not had a requirement for residential mechanical ventilation. It is also noteworthy that the IMC mechanical ventilation requirements are normally somewhat greater than the ASHRAE 62.2-2013 requirements, which generally average between 0.25 and 0.30 ach rather than 0.35 ach and do not require "approximately equal amounts of supply and exhaust air."

3.3 Airtightness and Whole House Ventilation Trends Discussion

While, as seen above, Code and program requirements are moving toward more airtight homes with mechanical ventilation, there are several important factors to consider as these changes are made including energy use and moisture impacts, which will be addressed here. Another important factor, combustion safety, will be addressed later in this report.

3.3.1 Airtightness and Whole House Ventilation Energy Use Considerations

One of the important considerations in determining airtightness and ventilation recommendations is energy use impacts. Research summarized below suggests only slight energy use impacts from airtightening in our climate in summer, and more significant impacts in winter. Ventilation will be discussed later in this section.

EnergyGauge USA modeling for a 2,000 square foot, 2010 Florida Code level home run for Orlando <u>without mechanical ventilation</u> and starting from an ACH50 of 10, showed annual energy savings of 333 kWh, 498 kWh and 661 kWh when ACH50 values were reduced to 5, 3, and 1 respectively.

An FSEC conducted multi-variate regression conducted for this project of monitored summer data from 58 mainly central Florida existing homes without mechanical ventilation indicated that at an 81% confidence level, for each additional ACH50, air conditioning energy use increased by about 0.5 kWh/day, or about 2% of total cooling energy use.

A recent monitored FSEC study (Parker et. al. 2014) of two side-by-side, central Florida non-mechanically ventilated lab homes did not find significant summertime energy savings from a tight (ACH50 ~2.2) central Florida lab home compared with an otherwise identical less airtight home (ACH50 ~8.0):

> *The comparative summer testing showed that tighter buildings…had little if any air conditioning (AC) energy savings…. The lack of energy savings in the tighter home was largely because the outdoor temperature was nearly as often below as above the desired thermostat set point. Thus, increased air infiltration during nighttime hours when the temperature outside is lower than the desired cooling set point actually reduces the AC load.*

While there is some difference in these two results, both indicate very small ACH50 influences on summertime energy use. The 81% confidence level of the 58-home study indicates that the true influence in a large sample of homes would likely still show up, but could be very small in terms of magnitude.

Turning to wintertime research, a multi-variate regression of winter data from the 58 non-mechanically ventilated home analysis for the three coldest days in January showed that at a 90% confidence level, heating energy use for heat pump homes increased by about 1.8 kWh/day or about 8% of total heating energy use for each additional ACH50. Winter results from the FSEC side-by-side lab home study (while the homes were not mechanically ventilated) showed a reduction in energy use for the tighter home in the range of 15.8%–18.6% relative to the leaky home (Vieira et al. 2013).

When mechanical ventilation is added there are a number of affects. First, outside air is brought in that needs to be conditioned. Second, the mechanical ventilation system uses energy. Third, depending on the system type, heat from the fan of the mechanical ventilation system is added to the space reducing heating needs but increasing cooling requirements. Thus, much or all of any savings from reducing air infiltration is used by the mechanical ventilation.

EnergyGauge USA modeling results for the same 2,000 square foot, 2010 Florida Code level home discussed above, but this time with energy (enthalpy) recovery mechanical ventilation using 0.75 W/cfm and maintained at 2013 ASHRAE Standard 62.2 levels are provided in Table 1, which shows minimal savings from increased airtightness.

Table 1. Modeled Annual Energy Use Savings for Various House Airtightness Levels with Mechanical Ventilation

ACH50	***EnergyGauge USA*** **Annual Clg+Htg+Vent (kWh)**
10	3,854
5	3,835
3	3,806
1	3,797
0.6	3,786

A different result was found however in a 2013 modeling study using an incremental ventilation energy (IVE) model (Logue et. al. 2013) showing significant airtightening energy savings (on the order of 1,000 kWh/yr going from typical DOE Weatherization Assistance Program level airtightness to ACH50 5) in our Florida climate with ASHRAE 62.2 levels of ventilation. Details as to power of the ventilation system and starting air tightness as an ACH50 level are not given by the study. The modeling was for older housing that had received typical weatherization program tightening.

The monitored FSEC side-by-side lab home study discussed above found significant increases in summertime cooling energy use when a supply-fan system was employed to provide mechanical ventilation to the tight (ACH50 2.2) home:

> *Unlike natural infiltration, mechanical supply ventilation revealed much more significant changes to energy use…when added to the tight home. Cooling energy increased by 20%–38% or about 4 kWh/day. Part of this increase resulted from the mechanical ventilation system fan itself, which added 1.8 kWh/day of energy use to the cooling system energy use.*

Another recent FSEC monitoring study involving six Gainesville Florida homes (Martin et. al. Pending Publication 2014) found that continuous exhaust ventilation (CEV) at approximately ASHRAE 62.2-2010 increased summertime cooling energy use by approximately 9% compared with runtime only, central fan integrated supply (CFIS) ventilation that provided approximately 20% of ASHRAE 62.2-2010 requirements (see Figure 1).

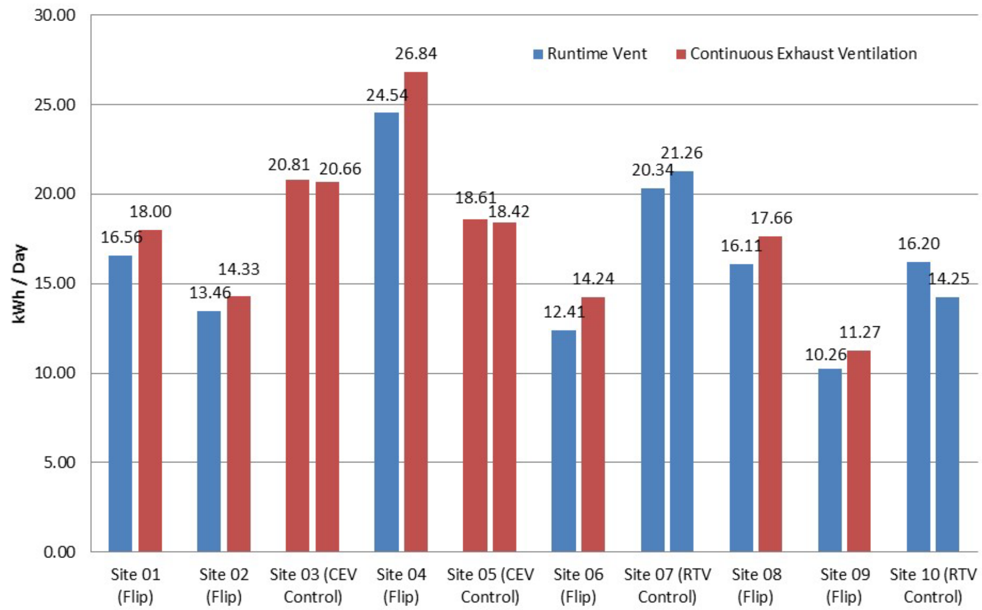

Figure 1 (figure and caption from Martin et al. publication pending 2014). Average HVAC energy use per day, broken into runtime vent (left bar) and continuous exhaust (right bar) periods. Sites 3 and 5 always operate with continuous exhaust, and sites 7 and 10 always operate with runtime vent.

As reported above, winter results from the FSEC side-by-side lab home study without ventilation showed a 15.8%–18.6% reduction in energy use for the tighter home relative to the leaky home, but when supply only mechanical ventilation was added to the tighter home, its heating use was 15% higher than the leaky home (Vieira et al. 2013). The increase in heating energy use for the tight home with ventilation prompted the researchers to note that heat recovery ventilation may have application to offset the increase.

While summertime results from the FSEC Gainesville study noted above showed energy savings for runtime only, central fan integrated supply ventilation compared to continuous exhaust ventilation, initial analysis of December 2013 through February 2014 data performed for this study indicate that the 100% ASHRAE 62.2-2010 continuous exhaust ventilation used for this study is consuming slightly less energy than the 20% ASHRAE 62.2-2010 runtime strategy in the winter. These results are being investigated further.

In a presentation at a 2012 Building America Expert Meeting (Cummings 2012), Jim Cummings provided an analysis comparing the costs and benefits of an ERV ventilated ACH50 5 Orlando home to that of an ERV ventilated ACH50 1 home in the same city. Both homes had ASHRAE 62.2-2013 ventilation, the ACH50 home requiring 37 cfm of outdoor air and the ACH50 home requiring 79 cfm of outdoor air. With all costs other than maintenance and repairs considered, including the cost of additional air tightening and a more expensive ERV for the tighter home, Cummings calculated a net savings of $50 per year for the tighter home and a simple payback of 50 years.

3.3.2 Airtightening and Whole House Ventilation Moisture Considerations

In addition to energy savings, another important consideration in determining airtightness and ventilation recommendations in our Florida climate is moisture. Summertime research summarized below shows that moderate differences in airtightness don't have a large impact on indoor moisture, but mechanical ventilation impacts can be more significant**.** In winter, the results below show definite moisture benefits from ventilation of tight homes.

In addition to a small amount of energy savings, summertime results for the recent FSEC side-by-side lab home study also found the tighter (ACH50 ~2.2) unventilated home had "only modest differences in moisture content under natural infiltration" compared with the less airtight (ACH50 ~8.0) but also unventilated home. Adding supply only mechanical ventilation to the tight house increased summertime moisture levels by 2% - 5%.

A 2014 Building America Expert Meeting summary (Rudd 2013) reporting on modeling work also concluded mechanical ventilation causes increases in indoor RH:

> *…mechanical ventilation, operated at the ASHRAE 62.2-2010 addendum r rate, in a 3 ach50 house, raises the annual median indoor RH by almost 10% RH compared to a 7 ach50 house without mechanical ventilation in Orlando. That is because infiltration drivers are generally weak in that climate during floating hours (when it is still humid outside and the cooling system is not removing moisture), but mechanical ventilation forces a minimum air exchange.*

An earlier monitored study involving 43 existing homes in warm-humid and mixed-humid climate regions of the United States (Rudd and Henderson 2007) also found continuous whole-house ventilation during periods of infrequent cooling demand to cause high humidity levels as after long cooling cycles the interior dew point would slowly approach the outdoor dew point.

While moisture issues may often be associated with summertime in Florida, winter conditions can also be problematic, particularly for tight homes.

The FSEC side-by-side lab home study, while noting some differences in the lab homes compared to typical Florida homes (little moisture capacitance, no window operation and the homes were only one year old), found higher wintertime dew points and moisture problems (see Figure 2) inside the tighter home (without mechanical ventilation) compared with the leaky home. Each home started with typical internal moisture gains for normal occupancy, but even with reduced internal gains the tight home had humidity issues:

> *Window condensation and mold growth occurred inside the tight home. Even cutting internal moisture gains in half to 6.05 lb/day, the dew point of the tight home was more than 15°F higher than the outside dry bulb temperature.*

Figure 2 (figure from Vieira et al. 2013). Condensation on north-facing window in unventilated tight lab house January 23, 2013.

Figure 3 further illustrates these moisture issues, showing an example January day where the dew point temperature is 10+ degrees higher in the tight house than the leaky house and is higher than the north-facing window temperature during the nighttime and morning hours.

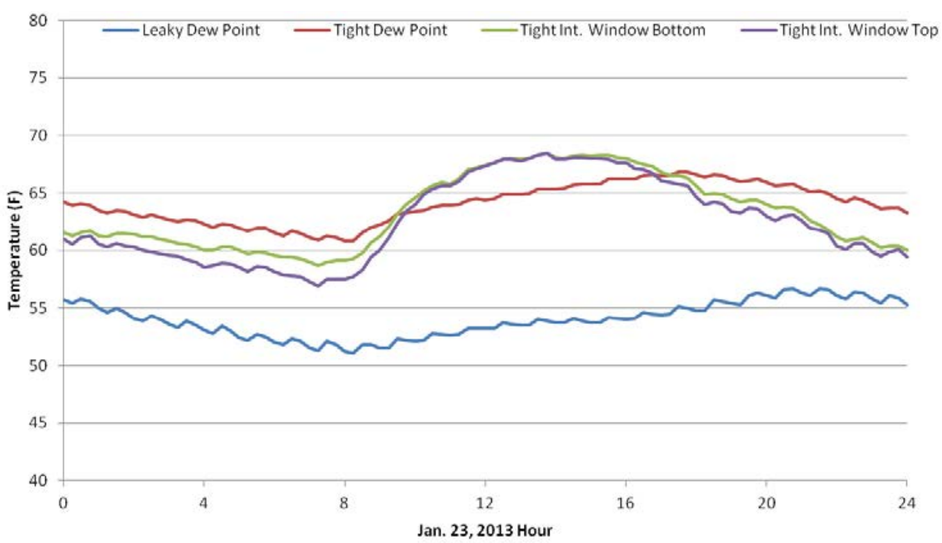

Figure 3 (figure from Vieira et al. 2013). Unventilated tight house dew point and interior window temperatures January 23, 2013.

As noted earlier, adding mechanical ventilation to the tight FSEC lab home raised heating energy use by 15%, but it also resolved winter moisture issues:

Winter condensation was observed again when the supply ventilation fan was off. Inside window temperatures (measured for the second winter collection period) were *lower than the inside dew point on cold winter nights. However, condensation was not observed when the ventilation fan was on, or in the leaky home.*

With the winter results from the FSEC lab home study indicating a risk of window condensation and high interior humidity levels in mind, the researchers also provided guidance for older Florida homes that are air tightened:

To reduce condensation potential there are steps practitioners may take coincident with tightening an older home. If the efficiency measures include window replacement, a low U-value for the window can be selected to avoid condensation. Also, mechanical ventilation can be introduced, which will likely reduce humidity in the home during winter. Judicious use of operable windows during mild periods with no space conditioning will also likely be helpful in reducing moisture problems.

3.4 Whole House Ventilation Options

As discussed earlier, the 2012 IMC, and by adoption the new 2014 Florida Mechanical Code, stipulate that ventilation air must be provided by "a method of supply air and return or exhaust air" and that the amount of supply air be approximately equal to the amount of return and exhaust air. Then Section R403.5.2 of the 2014 Florida Supplement (DBPR 2013) requires that residential buildings designed to be operated at a positive indoor pressure or for mechanical ventilation have a design ventilation rate of no more than the "design air change per hour minimums for residential buildings in ASHRAE 62, *Ventilation for Acceptable Indoor Air Quality*." Other than these requirements the new (2014) Florida Code does not address how the ventilation air is to be provided.

As noted in the introduction, the most widely encouraged and employed method for providing mechanical ventilation in homes across the United States is continuous exhaust. Throughout much of the United States exhaust ventilation does not create major problems. But this approach is generally not recommended in Florida because it can create excessive negative pressure which pulls warm moist air through the building's envelope. When this air is cooled while passing through the assemblies, condensation can occur on impermeable surfaces. **Combined with other factors beyond the control of the building code, such as homeowner thermostat set point and interior impermeable wall coverings, negative pressure ventilation has been found to cause mold growth in Florida homes and buildings** (Moyer et al. 2001). Figure 4 shows a mold covered wall that resulted from several factors including negative pressure bringing moist outdoor air into a wall cavity and impermeable wall coverings.

Figure 4. Mold covered wall resulting from a combination of factors including negative pressure and impermeable wall coverings.

Alternative methods of providing mechanical ventilation can produce positive pressure in homes. These systems involve a supply fan and duct, a balanced system or possible additional cooling systems. As such they are generally more complicated and more expensive than a simple exhaust system.

Table 2 provides a summary of whole-house mechanical ventilation options. Each can be used with humidity control strategies which are discussed in a parallel DBPR report (Withers and Sonne 2014).

Table 2. Whole-house Mechanical Ventilation Options

Ventilation Option	Description	Pros	Cons
Supply Only	Outdoor air is supplied into home via a small fan and single duct or multiple ducts to zones.	Low first and potentially low operation cost (depending on fan power use). Positive pressure drives conditioned air through envelope cracks and holes. Outdoor air can be filtered and conditioned (e.g. if dropped near air handler return).	Heat and/or energy (enthalpy) recovery not possible. Poor outdoor air distribution if single duct; also seasonally elevated RH where air is delivered.
Exhaust Only	Air is exhausted from home via single duct and small fan.	Low first and operation cost.	Negative pressure in home brings unconditioned outdoor air into home through building envelope; can lead to significant moisture related problems. Can also bring in air from undesirable locations such as the attic and garage. Heat and/or energy (enthalpy) recovery not possible.
Balanced with or w/o	Supply duct brings outdoor air into home	Balanced or positive house pressure possible. Outside	Energy recovery not effective at times in swing seasons.

Recovery	while exhaust duct remove indoor air.	air can be conditioned via heat or energy (enthalpy) recovery.	Uses two fans so twice as much energy use for ventilation. Higher first cost than exhaust or supply systems.
Runtime	Duct supplies outdoor air to return side of air handler.	Control strategies can limit excessive outdoor air and provide outdoor air at times where there is no call for cooling or heating.	Energy use of large air handler fan used to provide relatively small amount of air (can be minimized with variable speed air handler fan and high efficiency motors).

A 2014 ASHRAE humidity control options report (Henderson and Rudd 2014) provides an analysis of TRNSYS modeling results completed for the study:

> *Different ventilation systems have different impacts on relative humidity Levels. It is generally understood that different types of ventilation system (exhaust, AHU supply, and balanced) combine with infiltration to provide different overall ventilation impacts. We confirmed this finding here and also quantified the impact that different ventilation approaches had on the prevalence of elevated relative humidity. Exhaust ventilation was considered to be the baseline approach in this study. Central fan integrated supply (CFIS) slightly reduced high humidity hours compared to exhaust ventilation in Orlando and Atlanta. However, CFIS ventilation slightly increased high humidity hours in Miami and Houston because it provided more fresh air and because the part-time off-cycle operation of the AHU fan sometimes resulted in increased evaporation from the cooling coil.*

Recent FSEC work, described above and also discussed in FSEC's concurrent 2014 DBPR report on indoor humidity levels (Withers and Sonne 2014), compares indoor humidity levels for approximately ASHRAE 62.2-2010 continuous exhaust ventilation (CEV) with those of runtime only, central fan integrated supply (CFIS) ventilation that provided approximately 20% of ASHRAE 62.2-2010 requirements (Martin et al. publication pending 2014). In addition to the energy use results reported above, the monitored FSEC study involving six Gainesville Florida homes found continuous exhaust ventilation run at approximately ASHRAE 62.2-2010 rates raised summertime indoor RH by 5% compared with runtime only ventilation at approximately 20% of ASHRAE 62.2-2010 requirements.

Figure 5 from this Gainesville study shows that during periods when ASHRAE 62.2-2010 continuous exhaust ventilation was in use (right bars for sites 1, 2, 4, 6, 8 and 9) there were significantly more hours of indoor RH > 60% than during 20% of ASHRAE 62.2-2010 runtime ventilation periods.

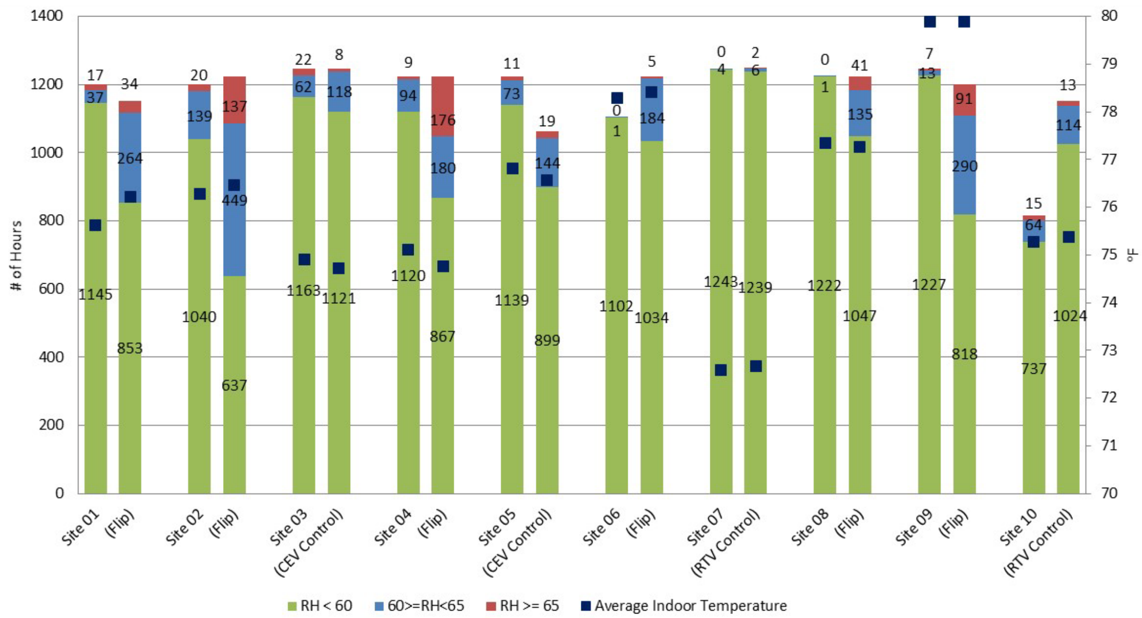

Figure 5 (figure and caption from Martin et al. publication pending 2014). Distribution of hours at various % RH ranges, separated into runtime vent (left bar) and continuous exhaust vent (right bar) periods, each corresponding to the left axis (# of hours). Numeric labels correspond to hours, black squares correspond to the right axis (average indoor temperature). Sites 3 and 5 were always operated with continuous exhaust ventilation, and sites 7 and 10 were always operated with runtime ventilation.

It is also informative to look at energy use of various levels of ventilation. A 2014 FSEC Building America program study (Martin 2014) modeled energy performance as a function of ventilation rate for a DOE Challenge Home level efficiency home for a number of US cities including Orlando Florida. *EnergyGauge USA* (EGUSA) runs were made with RH controlled to <60%. Figure 6 shows the energy use costs for

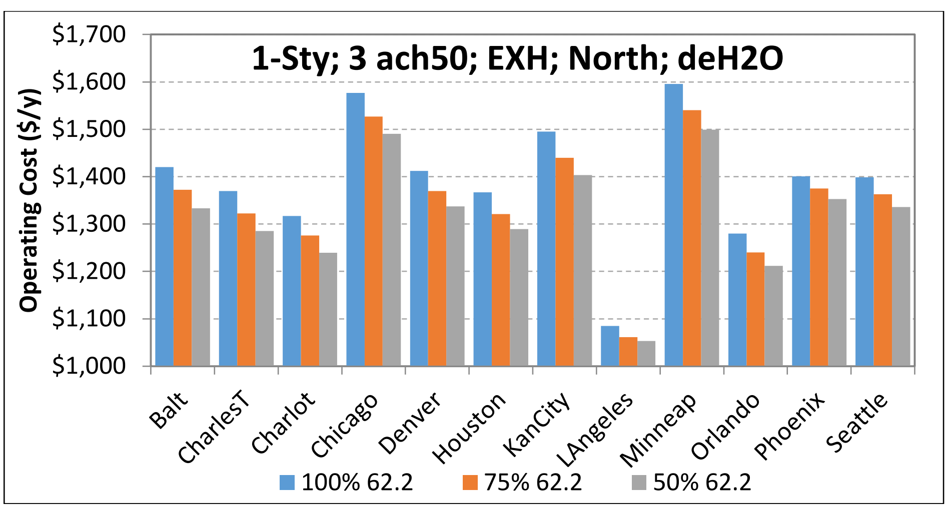

Figure 6 (figure and caption from Martin 2014). Total annual operating cost for a DOE Challenge Home controlled to <60% RH over a range of ventilation rates.

100% of ASHRAE 62.2-2013 ventilation and comparative costs when the ventilation rate is reduced to 75% and 50% of ASHRAE 62.2. Savings averaged over all the climates modeled were estimated at $45/year going from 100% of ASHRAE 62.2 to 75% and an additional $35/year going to 50%. Orlando savings are slightly less than the averages of the entire group.

3.5 Industry Airtightness and Whole House Ventilation Recommendations

A number of airtightness and ventilation practices and recommendations were found via the literature review.

The 2014 FSEC Building America program report noted above (Martin 2014) provided a summary of Building America teams' experience with ventilation approaches which is quoted extensively here:

> *Building Science Corporation (BSC) experience with whole-building controlled mechanical ventilation in tens of thousands of high performance homes in locations all across the United States has shown that drawing outdoor air from a known fresh air location, conditioning that air by filtration and sometimes heating or cooling, tempering that ventilation air by mixing it with central system return air, and fully distributing that air on at least an hourly average basis is a practical and effective way to mitigate odor complaints in all climates and an effective way to mitigate moisture buildup in mixed and cold climates. For more than 15 years, BSC builder partners have been installing systems capable of meeting more than ASHRAE Standard 62.2 ventilation rates, but typically running those systems at one third to one half that rate, resulting in satisfied builders and homeowners in both production and custom housing (Rudd and Lstiburek 1999, 2001, 2008). BSC attributes that satisfaction at the lower ventilation rates to the full distribution and whole-house mixing of outdoor air drawn from a known fresh air source with filtration (Hendron et al. 2006, 2007; Rudd and Lstiburek 2000; Townsend et al. 2009a, 2009b).*
>
> *BA-PIRC (formerly BAIHP) worked with site and factory builders constructing custom, production, affordable, and multifamily homes to implement supply-based mechanical ventilation through the introduction of outdoor air into the return side of centrally ducted, forced-air, space conditioning systems. This approach, combined with rightsized heating/cooling systems and properly operating bathroom and kitchen exhaust fans (ducted to the outdoors) has been implemented in thousands of homes, primarily in the southeastern United States, since 1997 and has effectively controlled odors, maintained comfort, and proven effective at minimizing wintertime moisture buildup (Chandra et al. 2008). Similar to BSC's approach, these systems draw outdoor air from a known fresh air location, filter the air, temper the air by mixing it with central system return air, and fully distribute the air. Systems have been commissioned to deliver approximately 30%–70% of ASHRAE Standard 62.2-2010 rates, enough to create a slight positive pressure in the home with respect to outdoors; however, only while the central HVAC system is running to satisfy a heating or cooling requirement. Therefore, operation of the ventilation system is intermittent, especially during periods of limited to no HVAC runtime. In the Southeast, these periods typically coincide with increased*

natural ventilation through more frequent window operation, and the system has gained the acceptance of homeowners and builders alike in terms of comfort, durability, energy consumption, and perceived odor and moisture control. However, most of these systems do not meet the whole-house mechanical ventilation requirements of ASHRAE 62.2-2010.

While concluding that "building tight and ventilating right remains the best advice," a 2012 BSC article (Straube 2012) also states:

A tight house is better than a leaky house, with a caveat: A tight house without a ventilation system is just as bad as a leaky house with no ventilation system—maybe worse.

The 2012 LBNL paper (Sherman and Walker 2012) continues this theme, adding recommendations as to when ventilation is necessary:

New homes are typically three times tighter than the existing stock and are sufficiently tight that new homes need designed ventilation systems in order to meet acceptable indoor air quality requirements. In new homes airtighness can be designed-in and energy efficient homes are at about 1 Air Change per Hour at a typical test pressure of 50 Pa ($ACH50h^{-1}$]) compared with about 3-5 ACH50 for typical new construction. At these tightness levels some sort of mechanical ventilation is required to provide acceptable indoor air quality.

The same LBNL paper (Sherman and Walker 2012) concludes:

Production builders in the US regularly build homes with leakage below 5 ACH50. Current construction techniques can get this as low as about 1 ACH50, but achieving lower levels, such as those required for Passive House require considerable extra effort and expertise and are unlikely to become common any time soon. Furthermore the energy benefits of achieving such levels may be minor, while the system robustness decreases.

Martin Holladay, in the 2013 Green Building Advisor web article (Holladay 2013), after stating that more research is needed in this area, still concludes:

I think it's wise for builders to install equipment that allows occupants to ventilate their homes at the rate recommended by ASHRAE 62.2 (7.5 cfm per occupant plus 3 cfm for every 100 square feet of occupiable floor area). However, that doesn't mean that every home in the U.S. needs to be ventilated at that rate.

A ventilation standard counterpoint is provided by Max Sherman of LBNL in another comment he made in the discussion section of the 2013 Green Building Advisor article:

Current ventilation standards are set based on engineering judgment by a room full of "experts", but some of us would like to see that transition to be based on a bit more causality and science. That is the direction my research has gone in the last few years.

The Future Ventilation Directions section at the end of this report provides additional information on this approach.

3.6 Whole House Ventilation Failure Concerns

As noted in the Introduction and in the above industry references, there are concerns related to mechanical ventilation failure in very tight houses. Mechanical ventilation system failure can create a number of potentially serious problems:

1) Decrease indoor air quality
2) Lead to moisture problems such as elevated indoor relative humidity and mold growth during cold weather (e.g., Florida in the winter)
3) Create unbalanced air flow causing combustion safety problems: when a house is very tight, various forms of unbalanced air flow (such as exhaust fans without make-up air, unbalanced return air, or duct leakage) can lead to depressurization of the interior space which can lead to spillage or back-drafting of vented combustion devices (hot water heaters, furnaces, boilers, and fireplaces). This can introduce combustion gases, including carbon monoxide, into the home and create health and death risk. Negative pressure can also produce flame roll-out and the potential for a house fire.

A 1999 Canada Mortgage and Housing Corporation (CMHC) field study (CMHC 1999) provides an example of the problems depressurization can cause:

> *In one house, the supply fan was not functioning. The homeowners were not aware of the problem because they still heard the sound of the exhaust fan. The result was backdrafting of the fireplace and the potential for backdrafting of other combustion appliances.*

A 2012 FSEC research report on airflow and water vapor drivers led by Jim Cummings (Cummings et al. 2012) provides additional tight house depressurization considerations:

> *Pressure differentials produced by unbalanced airflows from mechanical systems are exaggerated when a house is very tight. Consider, for example, that a clothes dryer exhausting 200 CFM from the house would produce negative pressure of –23 Pa in a 2000 ft^2 house with an airtightness of 1.0 ACH50. This level of negative pressure can cause slamming of doors and combustion safety problems such as spillage and backdrafting of vented combustion devices (e.g., gas furnaces, gas water heaters, fireplaces, and wood stoves), incomplete combustion accompanied by high carbon monoxide (CO) production, and flame rollout from water heaters. A cook-top grille exhausting 400 CFM would produce negative pressure of about –60 Pa in that same house.*

While sealed combustion equipment is becoming more popular in northern states, atmospherically vented combustion devices are still being installed. Mild Florida winters make high efficiency sealed combustion furnaces less cost effective, so atmospherically vented combustion equipment will continue to be in use. Atmospherically vented gas water heaters are also popular in the state and operate year round. As a result, the depressurization issues described above will continue to be an issue.

3.7 Whole House Ventilation Performance and Failure Research

Some research has also started looking at mechanical ventilation performance and failure rates.

Despite a survey showing occupants to believe ventilation is important for health, a 2002 Washington State research study (Lubliner et al. 2002) found significant problems with mechanical ventilation systems:

> *Only 29% (5/17) of the systems integrated with central heating systems complied with either the prescriptive or performance requirements of the code. … The field research data reveal that the technical details of the whole house ventilation requirements are widely misunderstood. Only 32% of all systems surveyed met VIAQ performance requirements. Exhaust systems not integrated with central heating were more compliant than other systems, complying with the code 71% (10/14) of the time (all prescriptively). Only 60% of those also met the performance airflow targets of the code.*

The 1999 CMHC field study noted above found 12% of heat recovery ventilators (HRVs) to not be operational due to component failure and also noted balancing issues, installation faults and a lack of homeowner understanding as concerns.

A soon to be published report from a major University in another state indicates that significant mechanical ventilation issues continue (Unreleased study, publication pending). Out of a sample of 29 mechanical ventilation systems inspected, fourteen had control issues, eight had dirty intakes, six had been installed incorrectly, and all 29 failed to have code-required display labels.

In a 2009 BSC *Top Ten Issues in Residential Ventilation Design* web article (Rudd 2009), Armin Rudd shares the following ventilation maintenance observations and recommendations:

> *Maintenance must be easy or it won't get done. Clogged air filters are probably the most common maintenance failure. Air filters must be easy to access. They should be either washable or readily available to purchase, preferably at the common home center stores. Outside air intakes that go through the first floor band joist are items that require annual cleaning. Avoid placing outside air intakes less than 12 inches or so off the ground. Parts that are expected to wear out and need replacement, like drive belts or moisture transfer cores, often don't get noticed when broken, or replaced when needed. Homeowners are usually less aware of maintenance needs for ventilation systems that are not part of the central space conditioning system. If the central space conditioning system fan stops, the system will surely receive the needed attention.*

To help address performance and failure issues, mechanical ventilation systems could be "locked in" with the space conditioning equipment, so that if it fails a homeowner or renter would need to have the system serviced. This solution however will be somewhat intrusive and cause some level of inconvenience, and there is the possibility of life-threatening consequences specifically in cold climates or on very cold days even in parts of Florida from the living space becoming too cold before the equipment can be serviced. Another possible means of alerting homeowners to a ventilation system malfunction is an alarm type system (similar to a home fire alarm).

The above referenced 1999 CMNC study, 2002 Washington State report and 2009 BSC residential ventilation web article all recommend ventilation system maintenance education, with the CMHC study also recommending additional installer education and offering maintenance agreements to homeowners, while the Washington State report also advocated "improved code language, and education of builders, contractors and building officials."

3.8 Health-Based Ventilation Considerations

As discussed earlier in this report, exhaust whole house ventilation is generally not recommended in Florida because the negative pressure pulls warm moist air through the building's enclosure. When this air is cooled while passing through the assemblies, condensation can occur on impermeable surfaces and elevated humidity can combine with other factors to cause mold growth. Beyond this consideration though, residential ventilation-health connections don't appear to be clearly established at this time.

The summary of an LBNL web article (LBNL 2014a) on this topic states:

> *Very little research has been conducted on the relationship of ventilation rates in homes with the health of the occupants of the homes. The results of a few studies suggest that children in homes with low ventilation rates have more allergic or respiratory symptoms compared to children in homes with high ventilation rates. There is also indirect evidence that ventilation rates of homes will affect health by modifying the indoor concentrations of a broad range of indoor-generated air pollutants.*

A 2013 Green Building Advisor web article on residential ventilation rates and health by Martin Holladay (Holladay 2013) puts it in a slightly different way:

> *Since experts have posited a connection between mechanical ventilation in homes and human health for the last 160 years, perhaps it's time to ask two questions:*
>
> - *Do we have any data that show a connection between residential mechanical ventilation and occupant health?*
> - *Do we know how much ventilation is desirable for optimal occupant health?*
>
> *The answer to the first question is no, not really. And the answer to the second question is an emphatic no.*

The author later goes on to explain his "no, not really" answer to the first question by stating that inferences between residential ventilation rates and occupant health can be made based on indirect evidence, and then quotes from an LBNL article related to the one noted above (LBNL 2014b):

> *From numerous experimental studies, as well as from theoretical modeling, we know that higher ventilation rates will reduce indoor concentrations of a broad range of indoor-generated air pollutants. Because exposures to some of these air pollutants, for example, environmental tobacco smoke and formaldehyde, have been linked with*

adverse health…, we expect that increased home ventilation rates will reduce the associated health effects.

Holladay then also states that limiting indoor pollutants is the most important thing to do. In a comment posting to Holladay's article, Max Sherman of LBNL shares a parallel thought:

Ventilation is principally about removing indoor-generated contaminants of concern. The more you can capture them at their source and the less you can distribute them to the occupants, the better it is.

4. TASK 2

The Task 2 goal is to develop alternative approaches to achieving acceptable levels of ventilation while avoiding the risks associated with super-tight home enclosures and potential mechanical system failures.

As indicated in the Task 1 section above, there is wide consensus that both controlling infiltration and providing mechanical ventilation is necessary for homes, but determining appropriate levels for each is much more involved.

While occupant health data related to ventilation are seemingly scarce, findings to date still include a rather broad consensus that ventilation systems should be able to provide ASHRAE 62.2 ventilation rates.

4.1 Recommendations

The 2012 FSEC airflow and water vapor drivers report referenced above (Cummings et al. 2012) addresses the pros and cons of tight envelopes verses relying somewhat on natural infiltration, concluding that section with the following:

A compromise between the two positions seems in order. Build it "reasonably tight" and provide mechanical ventilation. "Reasonably tight" might be 5 ACH50 in Florida and 3 ACH50 in Illinois, for example. In each of these locations, natural infiltration might fall between 0.10 to 0.20 ACH during most hours of the year. In case the ventilation system stops working, the house occupants will receive a substantial portion of the ventilation that they need. On the other hand, the envelope will be sufficiently tight so that natural infiltration will not exceed the ventilation requirements of ASHRAE Standard 62.2 for very many hours per year. And by producing a "reasonably tight" envelope, pressure differentials produced by unbalanced airflows will not be excessive.

This paragraph represented the authors' position going into this study. While, as summarized above, there are a number of factors to consider and varying industry recommendations, based on the totality of the research done for this project, the authors still maintain this original airtightness position to encourage "reasonably tight" Florida homes with neutral or slightly positive pressure mechanical ventilation.

Specific recommendations include:

- Do not require further airtightening beyond the 2012 IECC requirement for homes to have an air leakage rate not exceeding 5 ACH50 in Florida.

- Consistent with the 1995 recommendations, focus on airtightness between indoors and the attic, garage, and crawlspace instead of locations in the house envelope where the entering air would be of higher quality.

- The amount of airflow required in ventilation standards has limited health-related validation. A health metric needs to be incorporated into ventilation standards and to do that, building scientists and medical researchers will need to collaborate. Although such research will take a long time, it should be conducted as there are health consequences in the balance.

- To minimize risk of health consequences source control should be advised more regularly than present. The means of doing so is beyond the scope of this study, but the public needs better education of the risk of pollutant sources in homes. Furthermore, residents need education on storing certain materials and chemicals outside the home.

- Ventilation systems should be designed to have the following features:
    - Flexible airflow rate. As standards change and more health-related research is conducted, the recommended flow rates may change. Furthermore, a system with adjustable rates will allow for field or seasonal adjustments.
    - Highly efficient fans. The ventilation system will use power and there is a fair amount of variation in energy use of fans. Oversized fans that run on slow speed may meet the needs for flexibility while saving energy as the power curve of motors usually results in reduced Watts per cfm. Energy use for whole house mechanical fans of less than 0.2 or 0.3 Watts per cfm may be able to be specified in codes in the near future.
    - Be positively pressured or balanced systems. Positively pressured and balanced systems provide control of where the air entering the home is coming from and reduce risks of mold and mildew on surfaces.
    - Be installed with air intakes at proper locations. The 2014 Florida Energy Conservation Code Section R403.5.2 requirement not allowing ventilation air to come from "attics, crawlspaces, attached enclosed garages or outdoor spaces adjacent to swimming pools or spas" should be added to the IECC. Furthermore the intake should not be near insecticide spray locations, car exhaust, air conditioning condensers or dryer exhausts.
    - Have a means to remove humidity of the ventilation air. Another research project is currently exploring options (Withers and Sonne 2014).

- Recommended systems include an enthalpy recovery ventilation (ERV) system. Moisture of entering air can be reduced with these systems. The systems use balanced airflow which requires two fans so they tend to use more energy than supply or exhaust only systems. ERVs are popular in the national marketplace and can be set up to meet most of the requirements listed above. In addition to the energy use and first cost, key concerns of such systems are the maintenance of two fans and the enthalpy exchange media.

- Supply only systems can be combined with dedicated outdoor air systems, the standard home air conditioner, and/or dehumidifiers to remove moisture and can be purchased and installed at a low first cost (albeit, the dehumidification solution may become expensive). A popular method in high efficient homes has been runtime supply ventilation systems that run only when the AC is on. They do an excellent job of bringing in air and keeping humidity under control when the AC runs frequently. However, they may also need to cycle on during other times which may include days when outside air is damp but not hot so the air conditioner thermostat does not call for cooling or dehumidification; at these times they may bring in air that will raise the humidity in the home. (For example, a late season tropical storm in November.)
- Failure rates of systems in limited field studies raise concerns about the longevity and home resident operation and maintenance of whole-house ventilation systems. If residents think they are obtaining outside air but do not know the system has failed that could be a health concern. Consideration should be given to mandating some type of alarm if there is a detected failure (much like home fire alarms).
- A research project should be initiated to study the effectiveness and failure rates of whole-house mechanical ventilation systems installed in Florida over the last 15 years.

4.2 Future Ventilation Directions

There is currently work underway to try to incorporate a health-based approach into ventilation specifications. In a 2013 LBNL Q and A format article by Mark Wilson and Max Sherman (Wilson and Sherman 2013), Max Sherman of LBNL provides a summary of this direction:

> Q. *Of course, ventilation is a primary method for improving indoor air quality because it can reduce or dilute environmental pollutants. However, ventilation standards such as ASHRAE 62.2 don't consider specific removal of the priority pollutants. How would we benefit from revising the ASHRAE 62.2 standards to incorporate a health-based indoor air quality standard, and how might that work?*
>
> A. *ASHRAE 62.2 provides guidance for a ventilation rate based on a particular type of building and other factors, but a health metric isn't part of that calculation. Incorporating a health metric such as DALYs [disability adjusted life years] into the standard would allow designers and builders to consider the building materials used and other factors when determining ventilation rates. If it were clear that those factors showed lower indoor emissions, then a lower ventilation rate could be used; if not, you'd use a higher rate. ...*

In the same article Sherman notes that ASHRAE Standard 62.2 revisions are made on a three-year cycle and the health-based approach will be incorporated into the next (2016) version of the Standard.

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