Considerations for providing healthy, comfortable, energy-efficient whole-house mechanical ventilation during humid weather in near zero energy homes

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Abstract. Whole-house mechanical ventilation (WHMV) is necessary for adequate ventilation in healthy near zero energy homes in most cases. Ventilation standards such as ASHRAE 62.2-2016 call for more ventilation than can be provided by natural ventilation in new homes built better than minimal building code requirements. A very troubling matter is that different studies in different climate locations have shown that a majority of WHMV evaluated in occupied homes has found them to be turned off, broken, or delivering too little ventilation when operational. Some homes with adequate ventilation may have increased potential for comfort complaints, moisture control issues, and even higher than expected energy usage. Higher energy usage will occur when supplemental dehumidification is needed. Balanced ventilation provided through a heat recovery ventilator or an energy recovery ventilator may be a good approach for many climate zones, however supplemental dehumidification needed for homes intended to maintain relative humidity around 50% during mild humid weather. Recent studies found that the highest efficiency variable air conditioning systems do not dehumidify as well as lower efficiency single stage systems, but some may be capable of very good dehumidification negating the need for costly supplemental dehumidification. This paper will use recent lab and field research studies to discuss details of issues that engineers and builders must consider to design WHMV with good potential of providing healthy, comfortable and energy-efficient ventilation.

1. Introduction
Near Zero Energy Homes (near ZEH) are very airtight requiring indoor ventilation provided through mechanical means. While pollutant and moisture source removal from cooking exhaust hood and bathrooms is important, these are typically used as needed and do not provide the full amount of house ventilation. This paper addresses whole-house mechanical ventilation (WHMV) intended to provide fresh outdoor air to dilute indoor pollutants and odours. There different methods used to provide WHMV, any of which may be effective under specific circumstances. Balanced ventilation provided through heat recovery ventilator (HRV) or energy recovery ventilator (ERV) are good choices for near ZEH. An HRV tempers sensible heat content of outdoor air with exhausted indoor air and is most suitable in locations where moisture transfer is not significant. An ERV tempers sensible and some latent heat of outdoor with indoor air and is a good choice in locations that experience periods of humid climate.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 62.2-2016 is the ventilation standard used to establish ventilation rates for homes in the United States. This standard sets the total required ventilation based upon the floor area and number of bedrooms.

Some U.S. homebuilders or homeowners in humid climate regions have intentionally under-ventilated homes because of the concern of moisture problems experienced in homes without adequate dehumidification [1]. Consider that 0.0425 m³/s (90 cfm) of total outdoor ventilation air at 21.1°C (70°F)
dewpoint cooled to 12.8°C (55°F) dewpoint must remove 29.4 kg (64.8 lb) of water vapour each day requiring 20.7 kWh (70,680 Btu) of energy per day. Air conditioning cools and dehumidifies indoor air. Near ZEH with very low cooling loads do not require large central air conditioning and have limited run-time. The low cooling loads are not adequate to remove the total latent load of a home during humid weather conditions. This results in higher indoor RH, is less comfortable and may pose increased health and building degradation risks if RH levels remain elevated too long. While no national mandatory standard exists, ASHRAE has developed a position paper proposing that indoor air dewpoint should be maintained at 12.8°C (55°F) [2]. This indicates a target indoor RH of 50% if the indoor drybulb temperature is maintained at 23.9°C (75°F).

2. Challenges to energy-efficient WHMV

In most climates, WHMV air must be conditioned to maintain health and comfort, which requires energy use. Good design provides an adequate amount of ventilation without over-ventilating to minimize energy impacts. There is legitimate concern that the homebuilding industry and occupants are not yet prepared to manage the responsibility required by proper design, installation, operation and maintenance. Another challenge is in meeting the sensible and latent demands of WHMV into the space conditioning design using as little energy as possible. Different climates present different challenges to optimizing energy-efficient WHMV and space conditioning energy. Perhaps the most challenging is the warm moist climate such as the southeastern United States or southern coastal Asian regions because ventilation requires more energy to remove water vapour (latent energy) than energy to reduce air temperature (sensible energy).

2.1. Is WHMV providing adequate ventilation?

Most important for good health, if we make homes very tight, the WHMV must operate and be maintained correctly. Various studies in North America indicate that homes with WHMV are not likely delivering adequate ventilation, and this does not seem to be improving over time. A 1999 Canadian study of 60 HRV found that 12% were inoperable due to equipment failure and that operable units had air flow, poor installation or poor occupant understanding about operation as other issues [3]. A study of ventilation systems in Washington State homes in 2002 found only 32% met requirements [4]. A later study in Washington State homes published in 2014 found only 3% of 29 systems were adequate. It was found that 48% had control problems, 28% not properly maintained, and 21% were installed incorrectly [5]. A ventilation study of 21 homes in Florida published in 2016 found only 14% were capable of operating and delivering designed ventilation, but two of the systems were simply turned off by homeowners. This means only one home had a WHMV system that was found turned on, reasonably maintained and delivering intended airflow. Nearly 60% of the homes in this study were only three years old at the time and age was not a significant factor in deficiency. Twelve homes were capable of operating and five of these had significant maintenance and installation issues [1]. A current U.S. Department of Energy (US DOE) study on residential indoor air quality and ventilation systems located in the northwest and southeast, at this current time, supports that most homes with WHMV are not adequately ventilated. Nine homes had been tested so far in the southeast and only two WHMV were operable and delivered adequate air flow. Published studies in North America indicate the importance of improved contractor and occupant education about WHMV.

2.2. The outdoor air moisture load management challenge during humid weather conditions

The heating and cooling loads associated with the outdoor air must be managed properly. Cold dominated climates require heat to warm outdoor ventilation air for comfort, much of which may be provided by heat exchange using an HRV. Internally generated latent is often adequate for comfortable RH during dry cold weather. Hot or warm dry climates may also be able to provide much of the outdoor air conditioning through an HRV. Humid climates present an added challenge to adequate comfort and energy-efficiency given the potentially high amounts of moisture that must be removed from the outdoor air. ERV should be used where humid weather persists a few months or more. The ERV helps exchange sensible and latent energy of indoors with ventilation air, but can only exchange drier indoor air if cooling loads are large enough to provide dry air.
Table 1 presents some examples of psychometric calculations of sensible and latent cooling loads for three different weather conditions to explain why humid regions require more energy for effective RH control. The results are based on 0.0425 m³/s total ventilation rate occurring 24 hours per day at different summer conditions. This ventilation rate would meet the required ASHRAE 62.2 ventilation rate for a 186 m² home with three bedrooms, common for U.S. homes. Negative values in Table 1 indicate mechanical energy required for removal of heat from outdoor air to an indoor neutral condition of 23.9°C (75°F) and 12.8°C (55°F) dewpoint.

Table 1. Daily sensible and latent cooling energy shown with latent-phase change water volume.

| Example summer day | Daily average outdoor drybulb temperature / dewpoint temperature | Sensible energy (kJ (Btu)) | Latent energy (kJ (Btu)) | Total energy (kJ (Btu)) | Latent water volume litres |
|--------------------|---------------------------------------------------------------|----------------------------|--------------------------|------------------------|---------------------------|
| Hot / moist        | 28.3°C (82°F) / 23.3°C (74°F)                                | -17,548                    | -100,830                 | -118,377               | -39.3L                    |
| Mild / moderately  | 23.9°C (75°F) / 17.2°C (63°F)                                | 0.0                        | -35,045                  | -35,045                | -14.2L                    |
| moist              | 22.8°C (73°F) / 12.8°C (55°F)                                | 4,988                      | 0.0                      | 4,988                  | 0.0 L                     |

The examples shown in Table 1 demonstrate that the daily latent cooling mechanical energy required to dry outside air is greater than the sensible cooling energy during hot and warm moist weather. The latent energy required for hot moist conditions represents 85% of the total cooling requirement. During mild moist conditions, there may be no sensible cooling required, but energy is still required to remove the moisture from the air. This is a difficult challenge if only relying on air conditioning during low cooling loads. Typical thermostats only respond to the sensible conditions in a home, therefore under these conditions, the air conditioner runtime is inadequate to remove all the latent energy transported into the home. The result is higher indoor RH. Lowering thermostat settings will increase cooling runtime and remove some additional moisture, but not enough. The RH may be lowered somewhat, but overcooling is not an effective method to control RH down to 50% RH during humid weather [6]. This method causes increased energy use and colder temperature than desired.

2.3. The potentially high energy use of supplemental dehumidification

In a literature review and preliminary lab experiment on energy-efficient methods of indoor RH control in 2014 it was summarized that supplemental dehumidification used with very high efficiency central heat pump was the general recommendation at that time [7]. Building experts considered using dehumidifiers (DHU) as a cost-effective method based on an RH setpoint of 60%, which is higher than the 50% ASHRAE target [2]. Simulation of an energy efficient home indicated only modest supplemental DHU energy use of about 150 kWh/y for hot humid climate city such as Orlando, Florida in the U.S, but noted that this increased by about 5 times when the RH setpoint is 50% [6]. The relatively low first-cost and expected modest operational energy cost was cause for nationally recognized building science experts to recommend this as a cost-effective means to control RH in humid climate zones. However, given higher health and energy conservation expectations for near ZEH and a case made by ASHRAE to maintain around 50%, a 60% RH setpoint is on the border of best practice.

2.3.1. Dehumidifier energy increases significantly at setpoints below 60% RH

Controlled house laboratory research testing at the Florida Solar Energy Center Manufactured House Lab was used to compare DHU energy at two different RH setpoints. This 149 m² furnished laboratory test home had three bedrooms with automated interior sensible and latent heat loads. The test house had WHMV set at a constant 0.0260 m³/s (55 ft³/m). WHMV was a supply fan with no HRV/ERV. Air conditioning cooling efficiency had a Seasonal Energy Efficiency Ratio (SEER) efficiency rating of 23.2 kJ/Wh (22 Btu/Wh commonly noted as “SEER 22”). The DHU capacity was rated at 33.1 L (70 pints) per day with an energy efficiency rating of 1.85 L/kWh. More testing details with the DHU RH
setpoint at 60% can be found in the final report [8]. Similar testing was repeated later except with the DHU RH set at 50%. The daily measured DHU energy use was compared with RH setpoints at 60% and 50% during similar warm and humid outdoor conditions with daily average temperature of about 25.0°C (77°F) and 20.6°C (69°F) dewpoint. The measured DHU daily energy increased from 0.483 kWh to 4.610 kWh (9.5 times greater) when changing the DHU setpoint from 60% RH to 50% RH as a result of the increased moisture demand upon the DHU set at the lower RH setpoint.

2.3.2. Annual space conditioning energy simulation of near ZEH results for three different climate zones
A simulation effort conducted for this paper to investigate the annual dehumidification energy use in near ZEH with ASHRAE 62.2 ventilation in three different climate zones that experience humid weather. The energy simulation software used EnergyGauge USA [9] to evaluate the annual space heating, cooling and DHU energy use for three different climates zones that experience different amounts of humid weather and cooling loads. The annual simulation software is currently one of three nationally accredited Home Energy Rating System (HERS) software programs approved for predicting annual energy use in high-performance home programs in the United States of America.

Each one-story single-family home was 186 m² and had efficient construction, ERV/HRV ventilation, ENERGY STAR efficient appliances, and LED lighting. Space conditioning was provided by a heat pump with SEER 23.5 Btu/Wh cooling and Heating Seasonal Performance Factor (HSPF) 10.2 Btu/Wh heating efficiency. The 33.1 L (70 pint) per day DHU had a very high efficiency rating of 2.4 L/kWh. The simulation program calculated cooling, heating and DHU loads for each hour of the day over a full year using Typical Meteorological Year (TMY3) data for the chosen location. Calculated energy accounted for the input efficiency of each system. The same programmable thermostat setting were used in all homes with cooling setpoint at 25.6°C (78°F) set up to 26.7°C (80°F) from 9AM-2PM. Heating setpoint was 20.0°C (68°F) adjusted down to 18.9°C (66°F) from 11 PM-5AM. The input DHU control started DHU at 50% RH and stopped at 45% RH. Table 2 shows the annual energy use for space heating, cooling, dehumidification and WHMV energy. The total home energy includes all home operational energy including all space conditioning, mechanical fan ventilation, interior and exterior lighting, major appliances and 1820 kWh/year of miscellaneous energy. The Orlando and New York home would need about 7500 W of photovoltaic panels to have near zero energy use and the Portland location in the Pacific Northwest would require about 8500 W. The simulation results show potentially high-energy use of DHU depending upon climate. DHU are available on the market with half the efficiency simulated here and could use much more energy than shown in Table 2.

### Table 2. Simulation of annual space conditioning and total home energy usage.

| Location          | Heat energy kWh | Cool energy kWh | DHU kWh | WHMV kWh | Total home kWh | Total home kWh/m² |
|-------------------|----------------|----------------|---------|----------|----------------|------------------|
| Orlando, Florida  | 71             | 1416           | 2685    | 419      | 10726          | 57.7             |
| New York, New York| 741            | 1244           | 652     | 362      | 9685           | 52.1             |
| Portland, Oregon  | 595            | 515            | 1537    | 296      | 9671           | 52.0             |

2.4. Air conditioner rated efficiency does not indicate moisture control performance
Simulation indicated high DHU energy use in humid climates. Field and lab research was conducted to learn more about moisture control in energy-efficient homes that use very high-efficiency air conditioners in the humid climate of Florida. A study of four energy-efficient homes with variable-capacity high-efficiency air conditioning systems capable of operating with periods of high SHR resulted in homes with indoor RH exceeding 60% RH for significant periods of time [10].

It helps to understand this by explaining a few fundamentals about cooling and efficiency rating. U.S. air conditioner efficiency is rated under a limited set of conditions to provide a relative method for consumers to compare expected energy use; however, resulting indoor air RH is not considered in such rating tests. An air conditioner not only cools the air, but it also dehumidifies it, and dehumidification performance can vary significantly for different systems having the same efficiency rating. The energy applied towards reducing sensible air temperature as a ratio to the total cooling energy used is known as
the sensible heat ratio (SHR). A review of manufacturer published cooling performance data found some air conditioners with a SEER 30 efficiency occurred at SHR of about 0.9. In this case, 90% of the energy cools air temperature and only 10% removes water vapour (latent energy). Systems operated at high SHR remove very little moisture, and are the wrong choice for properly ventilated homes in humid climates. High SHR is very efficient and a good choice for warm/hot drier conditions.

2.4.1. Lab testing demonstrates that RH control is important consideration in space condition energy

Very high efficiency variable capacity air conditioners commonly offer “dry” or “RH control” mode of cooling; however, no published studies have shown they can adequately control RH without DHU to maintain indoor RH below 60% in properly ventilated homes during low-load humid conditions. The house lab testing arrangement previously mentioned in section 2.3.1 also tested space cooling and DHU energy using variable-capacity cooling systems with minimum and very high efficiency. One test used a SEER 14 rated cooling system with enhanced dehumidification control characteristics that allowed operation at lower SHR. The second test used a SEER 21.5 efficiency system. Each system operated several weeks with the supplemental DHU set at 50% through a variety of weather conditions [11]. A least-squares regression analysis of the space cooling and supplemental dehumidification daily total energy versus the daily average difference in temperature between outdoors and indoors was completed. Results were statistically significant at 95% confidence and $R^2=0.71$ for SEER 21.5 and $R^2=0.95$ for SEER 14. Figure 1 shows daily total energy shown for a range of outdoor temperatures. Regression analysis was used to calculate energy based upon indoor temperature of 24.4°C (76°F).

![Figure 1](image-url)

**Figure 1.** Daily total cooling and DHU energy at specific outdoor temperatures shown with DHU % of total.

The results showed that the lower rated efficiency air conditioner and DHU used less total energy than the high efficiency unit and DHU used. With some improvement to thermostat algorithm control, the SEER 14 system would not need a DHU at all. The SEER 21.5 air conditioner removed less moisture and required much more dehumidification under moderate to low cooling loads. Once daily average temperatures exceed about 24°C (75°F), the SEER 21.5 cooling energy savings made up for DHU and began using less total energy. These results demonstrated that variable capacity SEER 20+ units should be able to run at very efficient operation when dehumidification is not needed, and with some improvement, be able to operate a dehumidification mode that lowers SHR and removes moisture more efficiently than a DHU. Evaluation of a few systems indicated that improvements to algorithm control in RH modes could provide adequate RH control to near 50% RH during low cooling load periods.

The house lab testing results under realistic indoor and outdoor conditions, demonstrated that solely considering cooling efficiency ratings are not adequate in realistic total space conditioning energy for locations that experience humid weather. Furthermore, there is no current energy rating or evaluation procedure adequate to assure indoor RH will be maintained reasonably. Supplemental DHU energy use is not considered by the U.S. HERS and does not reflect realistic predictions of total house energy use when DHU is considered to be used.
3. Conclusions

- North American studies demonstrate that near ZEH with whole-house mechanical ventilation are not adequately ventilated and homebuilder and occupant education is needed.
- Proper ventilation and humidity control are critically important. Ventilation air introduces significant amounts of moisture during humid weather that must be removed to control RH.
- Some experts recommend indoor RH limited at 60% RH. This compromises optimum health control with decreased energy use. RH at 50% offers better assurance of air quality.
- Supplemental dehumidification energy increases significantly at setpoints below 60% RH.
- Very high efficiency air conditioners that operate at high SHR will have poor dehumidification, higher indoor RH, and require more DHU energy to control RH. Annual DHU energy can exceed cooling energy in near ZEH located in warm humid climates.
- Engineers must consider the cooling sensible and latent loads based on local conditions and plan for DHU energy at the design stage.
- The RH control cooling modes of variable capacity efficiency SEER 22 modestly reduced RH, but still required DHU to control RH below 60% during humid low cooling load conditions.
- Testing indicated that very high efficiency variable capacity heat pump systems should be able to improve RH cooling modes in the near future to be able to control indoor RH near 50% without requiring costly DHU energy use.

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