Infiltration and Ventilation in a Very Tight, High Performance Home

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ABSTRACT

The Net Zero Energy Residential Test Facility (NZERTF) was constructed at the National Institute of Standards and Technology (NIST) to support the development and adoption of cost-effective net zero energy designs and technologies. Key design objectives included providing occupant health and comfort through adequate ventilation and reduced indoor contaminant sources. The 250 m^2 two-story, unoccupied NZERTF was completed in 2012 with the following design goals: meeting the comfort and functional needs of the occupants; siting to maximize renewable energy potential; establishing an airtight and highly insulated building enclosure designed for water and moisture control; providing controlled mechanical ventilation; and installing highly efficient mechanical equipment, lighting and appliances. The NZERTF achieved its goal of generating more energy than it consumed during its first year of simulated occupancy by a single family, despite a severe winter at the building site. The airtightness goal was achieved through detailed envelope design, careful construction, and during- and post-construction commissioning techniques. The NZERTF is one of the tightest residential buildings in North America with a whole building pressurization test result of roughly 0.6 h^{-1} at 50 Pa. The ventilation goals were met with a heat recovery ventilator sized to comply with ASHRAE Standard 62.2-2010, which corresponds to roughly 40 L/s or 0.1 h^{-1} for this building.

This paper describes the design and construction methods used to achieve such a tight building as well as the performance measurements made to verify that the building achieved its airtightness and ventilation goals. Tracer gas measurements of air change rates are reported, as well as multizone airflow model predictions of these same rates for comparison. This study highlights some of the measurement and modelling challenges in very tight buildings.

KEYWORDS

Airtightness; netzero energy; residential; ventilation.

1 INTRODUCTION

Residential buildings in the U.S. and other countries have historically been ventilated by infiltration, supplemented by window openings and local exhaust ventilation. As energy efficiency has become a priority, buildings were built to be more airtight and mechanical ventilation started to be used to meet building ventilation requirements. The U.S. was slower in making these changes compared to some countries, particularly the Nordic countries in Europe, but U.S. homes are getting tighter (Chan et al., 2013) and mechanical ventilation is becoming more common (Persily, 2015). It goes without saying that infiltration is not a very good way to ventilate a building as the rate and air distribution is not controlled, the entering air is not be filtered for outdoor contaminants or dehumidified, and the rates tend to be highest during more severe weather when the energy penalty is greatest. Mechanical ventilation allows the rates to be controlled and the incoming air to be treated, as well as providing the opportunity for heat recovery. In general, mechanical ventilation will provide better performance when combined with a tight envelope, or in the words of Arne Elmroth “Build tight, ventilate right” (Elmorth, 1980).

The Net Zero Energy Residential Test Facility (NZERTF) was built on the campus of the National Institute of Standards and Technology to demonstrate low energy residential technologies with the goal of netzero energy use on an annual basis. This paper describes the design and construction methods used in the NZERTF to achieve a very tight building with reliable mechanical ventilation, as well as the results of selected performance measurements in the building. This study highlights some of the measurement and modelling challenges in very tight buildings.

2 DESIGN AND CONSTRUCTION OF THE NZERTF

The NZERTF is a 250 m^2 two-story, unoccupied house located in Gaithersburg, Maryland with an unfinished basement and an attic, both within the conditioned space. The building envelope was constructed using advanced framing techniques (i.e., studs of greater depth than typical of U.S. construction, allowing for more insulation to be installed) with a continuous fully-adhered membrane air and moisture barrier sealed down to the foundation wall (Figure 1). The nominal R-value of the wall assembly was R-7.9 $m^2 \cdot K/W$. The roof insulation was part of the roof structure, a nominal R-value of R-12.7 $m^2 \cdot K/W$. A 10.2 kW photovoltaic system was located on the main roof. Four solar thermal collectors were located on the roof of the front porch to provide domestic hot water. More details on the building design and construction can be found in Pettit et al. (2014). Internal loads, energy and water usage of a virtual family of two adults and two children were simulated according to daily schedules (Omar and Bushby, 2013). Sensible heat from the occupants was simulated throughout the house, while the latent loads were located only in the kitchen. Energy performance results for the first year of operation of the house, which demonstrated that the facility achieved better than net zero energy, are found in Fanney et al. (2015).

While the NZERTF was designed with several heating, ventilating, and air conditioning (HVAC) options for future research purposes, only a two-speed air-to-air heat pump with a dedicated dehumidification function has been used to date. Ventilation was provided continuously by a heat recovery ventilator (HRV) with dedicated ductwork. It supplied air to the living room on the first floor and the three bedrooms on the second floor. The air returned to the HRV was drawn from a bathroom on the first floor and two bathrooms on the second floor. It was sized to comply with ASHRAE 62.2-2010 (ASHRAE, 2010) which corresponds to roughly 40 L/s. Based on the available HRV fan settings, the actual ventilation supplied to the house was 56 L/s, as measured by duct traverse. It is interesting to compare the ventilation rate based on Standard 62.2 with the requirement based on other standards. For example, the historical ventilation requirement for residences in Standard 62, which last appeared in 62.1-2001, was 0.35 h^{-1} or 123 L/s. A recent review of residential ventilation requirements in Europe showed that several countries require 0.5 h^{-1}, which equals 176 L/s for the NZERTF (Dimitroulopoulou, 2012). It is worth noting that a literature review of ventilation rates and health found that air change rates about 0.5 h^{-1} have been associated with reduced risk of allergic symptoms in children in Nordic climates (Sundell et al., 2011).

Figure 1. Construction of NZERTF showing the air barrier (top) and completed structure (bottom).

Indoor air quality (IAQ)-based guidelines were developed for this project to support the design goal of providing good IAQ in this low-energy residence, in particular to guide the selection of interior finishes and insulation. The guidelines were mostly prescriptive, requiring use of certain builder installed products and avoidance of others, with the objective of reducing common sources of volatile organic compounds (VOC) that affect health and comfort. Emphasis was placed on reducing sources of formaldehyde emissions based on its known health impacts (IARC, 2012). Reduced emissions of VOCs in solvents were addressed by incorporating maximum VOC content requirements for wet-applied products. Guidelines were also included for adhesives and sealants, paints and coatings, built-in cabinetry, woodwork, doors, countertops, floor coverings, and insulation. As a result of careful material selection, the formaldehyde levels measured in the NZERTF over the course of eight months were on average 80 % less than the average measured in other new homes and 60 % less than the average measured in existing homes (Poppendieck et al., 2015). Levels of acetic acid, toluene, and other VOCs were also lower on average than in new and existing homes. These measurements also showed that when the HRV was off, steady-state concentrations of selected VOCs could rise nine times higher than outdoors. Note that the house contained no furniture, which is another source of VOC emissions. The NZERTF IAQ guidelines have been updated and formalized into a detailed architectural specification intended for use in new residential construction and major renovations. This specification is written in a manner so that it can be applied to any project and is available in Bernheim et al. (2014).

3 AIRTIGHTNESS, INFILTRATION AND VENTILATION MEASUREMENTS

The airtightness and ventilation rates of the NZERTF were measured to verify its performance relative to its design goals.

3.1 Envelope Airtightness

Five blower-door tests were performed at the NZERTF to confirm that the envelope airtightness met the design targets (Figure 2). The first three tests (without windows, pre-drywall, and substantial completion) were conducted by third-party testing companies (Pettit et al., 2014). The final tests (#4 and #5) were performed by NIST after the house was complete, according to the methods in ASTM E779-10 (ASTM, 2010). These results have an uncertainty of about 10 %. Test #4 was performed with the kitchen and dryer vents sealed and yielded an airflow rate of 195 L/s at 50 Pa, which corresponds to 0.55 h^{-1}. Test #5 was performed with those vents unsealed, yielding 223 L/s at 50 Pa or 0.63 h^{-1}. This airtightness value is compared with several guidelines in Table 1 and is tighter than the requirements in LEED and ENERGY STAR and slightly leakier than the Passiv Haus requirement. The Normalized Leakage value for the house equals 0.06. Based on statistical analysis of Lawrence Berkeley National Laboratory Residential Diagnostics Database (ResDB) by Chan et al. (2013), the NZERTF is tighter than well over 99 % of U.S. homes.

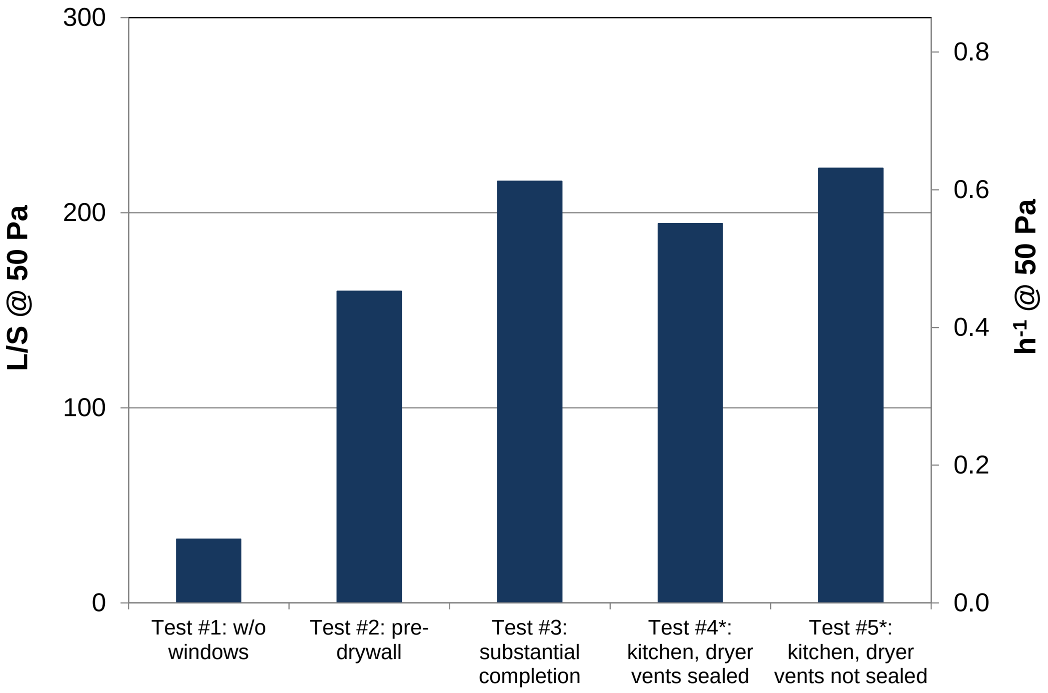

Figure 2. Blower door test results at various stages of construction. * indicates the tests performed by NIST

Table 1. Summary of NZERTF airtightness and relevant guidelines for airtightness

Guideline/Standard	**Target Airtightness (L/s at 50 Pa)**
NZERTF Design Target	381
DOE Challenge Home (DOE, 2013)	953
ICC 700 National Green Building Standard (testing option) (NAHB/ICC, 2012)	2648
LEED BD+C: Homes v4 (for 2 points) (USGBC, 2014)	706
ENERGY STAR v3.1 (rev. 06) (EPA, 2015)	1059
Passiv House (PHI, 2015)	212

3.2 Infiltration

The total outdoor air change of the NZERTF was measured on several occasions using tracer gas decay (ASTM, 2011) with the HRV on continuously and with it off. During these measurements, the heat pump and its air distribution fan were controlled by the thermostat. Measurements were made in July 2014, August 2014 and January 2015. For the summer measurements, with an average indoor temperature of 27 °C, an average outdoor temperature of 23.0 °C and an average wind speed of 1.6 m/s, the average outdoor air change rate with the HRV on was 0.17 h^{-1} and 0.02 h^{-1} with the HRV off. In the winter, with an average indoor temperature of 21 °C, an average outdoor temperature of -2.9 °C and an average wind speed of 2.9 m/s, the average outdoor air change rate with the HRV on was 0.19 h^{-1} and 0.06 h^{-1} with the HRV off.

The fan off air change rates were obviously very low, which raises questions regarding their measurement accuracy. The ASTM tracer gas dilution standard E741 (ASTM, 2011) states that the uncertainty associated with these measurements is 10 %. That standard also notes that the lower the air change rate, the longer the decay measurement required to achieve this uncertainty. For air change rates on the order of 0.03 h^{-1}, the standard suggests that decay tests need to last on the order of 24 h. The measurements reported on here, and in most field studies, rarely last more than a few hours, which presents a challenge when measuring such low air change rates. It is also worth noting that even with essentially zero indoor-outdoor temperature difference and a very low wind speed, the tracer gas decay measurements yielded a non-zero air change rate. It is unclear if these results were a result of the measurement uncertainty or if they reflected physical mechanisms inducing air change beyond the traditionally considered stack and steady-state wind effects. Previous measurements, dating back decades and performed in much leakier buildings, have shown nonzero air change rates even when there are very low driving forces. Regardless of any questions regarding the accuracy of these measurements and the values measured under very mild weather conditions, the infiltration rates are quite low.

3.3 Ventilation

As noted earlier, the HRV in the NZERTF was sized to comply with ASHRAE Standard 62.2-2010 (ASHRAE, 2010), which corresponds to roughly 40 L/s or 0.1 h^{-1} for this building. The airflow through the HRV was measured periodically using a hot wire anemometer (accuracy ±3 % or 0.015 m/s), yielding an average flow of 56 L/s. The airflow of the HRV supplies and returns were measured using a balometer, with a stated uncertainty from the manufacturer of ±3 % plus 2.5 L/s. Table 2 summarizes these measurements, along with the exhaust airflows associated with the kitchen exhaust and the clothes dryer, also measured with the balometer. The sums of the HRV supply and return vents match within their measurement accuracy but are below the values measured at the unit itself, which is likely a reflection of the measurement uncertainties of the flows, particularly for the balometer measurements at the individual vents, as well as the existence of duct leakage. Measuring such low airflow rates in the field is known to be challenging, and a previous study has recommended development of a measurement standard that takes “real world” conditions into account (Stratton et al., 2012). It is worth noting that the measured envelope infiltration rates, even in this extremely tight house, are on the order of 15 % to 40 % of the HRV ventilation rate based on Standard 62.2.

Table 2: Measured System Airflow Rates

Heat Recovery Ventilator	Supply	Return
1st Floor	15	19
2nd Floor	30	27
SUM	45 (0.13 h^{-1})	46 (0.13 h^{-1})
Ducts at HRV unit	56 (0.16 h^{-1})	54 (0.15 h^{-1})
Local exhaust		
Kitchen hood	49	
Clothes dryer	47	

* All flows in L/s except where otherwise indicated.

4 MULTIZONE MODELING

A CONTAM (Walton and Dols, 2013) model was created of the NZERTF using as-built documents and on-site system airflow measurements. On average, the difference between the measured air change rates measured by tracer gas decay and the model predictions were roughly 15 %. Based on the physical theory on which CONTAM and other multizone airflow simulation tools are based, an air change rate of zero is predicted when the wind speed and temperature difference are both zero. As noted above, nonzero air change rates were measured under these conditions and it is not clear whether these were measurement artifacts or reflect actual airflow dynamics. The prediction of air change rates with low driving forces, particularly in such tight houses, is another challenge in characterizing airflow in such houses that merits additional study. However, when considering very tight houses with very low infiltration rates, the accuracy of the predicted rates are generally less important than in leakier buildings.

5 CONCLUSIONS

Infiltration and ventilation of residences has been studied for decades, with trends towards the mantra of “build tight, ventilate right.” The design and construction of the NZERTF was consistent with that philosophy, resulting in a very tight envelope and controlled mechanical ventilation. The airtightness and ventilation measurements in this facility identify challenges for very tight homes, including appropriate airtightness limits and the accuracy of measurements at very low airflow rates. A range of airtightness target values exist, as described in this paper, and it is not clear how tight net zero or near-zero energy, high-performance homes really need to be. Also, even for this extremely tight house, the measured air change rates with the HRV off are still on the order of 15 % to 40 % of the air change rate due to the HRV. Even in this very tight house, the remaining infiltration is nontrivial compared with the intentional ventilation rate supplied in accordance with industry standards. It should also be noted that ventilating right in very tight homes is critical to maintaining acceptable IAQ since such low infiltration rates will not be able to adequately maintain indoor levels of contaminants.

6 ACKNOWLEDGEMENTS

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