

HEAT AND NON-HEAT RECOVERY VENTILATION PERFORMANCE IN ENERGY-EFFICIENT HUD-CODE MANUFACTURED HOUSING

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ABSTRACT

The Zero Energy Manufactured Home Project demonstrates and promotes innovative energy saving technologies to the manufactured housing industry and home buying public, while evaluating those technologies' energy performance. The project, funded by the Bonneville Power Administration, and the U.S. Department of Energy's (DOE) Building America Industrialized Housing Program (BAIHP), examines two 147 square meter (m²) (1600 ft²) two-section manufactured homes, built by the same manufacturer, using an identical floor plan. Heating ventilation and air-conditioning (HVAC) measurements, envelope and duct leakage tests were conducted and remote monitoring equipment installed to track the performance of each home over a three year period.

Both homes were built in the summer of 2002 and sited in the cold, dry climate of Lewiston, ID. The Zero Energy Manufactured Home (ZEMH) has been built with highly efficient and cutting edge technologies including a photovoltaic system, sun-tempering, solar water heating, spray-in foam insulation, heat recovery ventilation, and Energy Star appliances, HVAC and lighting. The comparison (ESTAR) home is built to Energy Star Program requirements as part of the Northwest Energy Efficient Manufactured Home program, which includes a quiet 20 watt whole house exhaust fan ventilation system. Energy Star is the most energy efficient home that meets the U.S. Department of Housing and Urban Development code available in the United States market today (NEEM).

This paper presents the field testing and monitoring results of both homes' heat recovery (HRV) and non-heat recovery (NHRV) ventilation system energy performance, based on in-situ monitoring data. Energy Gauge USA computer simulation software is used to compare the ventilation, envelope and duct leakage induced infiltration in the ZEMH and ESTAR homes. Anecdotal and occupant related observations are presented, along with some conclusions.

KEYWORDS

Heat recovery ventilation, indoor air quality, energy efficiency

INTRODUCTION

More than 200,000 factory homes are built in the United States each year to the federal manufactured housing standards (HUD 1994). Issues related to energy efficiency, heating, ventilation and air-conditioning standards and performance in these homes has been presented in previous AIVC papers (Lubliner 2000, 2003), (Persily 2003).

HUD code manufactured homes tend to be built tighter than site built homes, which is why codes require whole house mechanical ventilation systems. (HUD 1994), (TenWolde 1996), (Stevens 1997). HUD requires ventilation systems capable of ventilating the ZEMH and ESTAR homes be at least 26 liters per second (l/s) (56 ft³/min). For these homes the sizing approach in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62 (ASHRAE 2003) would require a comparable 29 l/s (61 ft³/min).

The ZEMH was built with energy efficiency and renewable energy as a high priority, in an effort to evaluate proposed future energy efficiency targets. The BAIHP targets seek to demonstrate future whole house energy savings of 60-70 percent over current practice, while improving indoor air quality and durability. (Lubliner 1994) Energy modeling of the ZEMH suggests that it achieves the 60 percent target. The ESTAR home achieved the current BAIHP 30 percent target. Analysis that compares modeled and actual total and end-load technology energy use in ZEMH and ESTAR home is currently under way.

HVAC System Descriptions:

Heat Pump: Both the ZEMH and ESTAR homes are all-electric homes with HVAC systems located in the utility room. They both have 7 kilowatt (kW) (2 ton) ducted unitary air-to-air heat pumps with electric resistance backup. All heat pump components, including the outdoor coil, are located inside a small closet in the house. The heat pump draws air from the crawlspace, directs it across the outdoor coil, and exhausts it through the ceiling and roof cap. Investigations are currently under way to determine the heating and cooling performance of the heat pump compared with typical split system heat pumps and electric furnaces.

Ductwork: The heat pump duct system has a single return air grill located in the utility room. Supply ducts distribute conditioned air to floor registers in the other rooms via *riser* and *trunk* ductwork located above the floor insulation as shown in Figure 1. A *crossover duct* in the vented crawlspace connects the trunk ducts of the two home sections. The use of duct mastic and air-tight Icynene™ foam floor insulation in the ZEMH ensures that the supply riser and trunk ducts are airtight and well within the indoor pressure and insulation boundary with minimal heat transfer between the house and the crawlspace. The ESTAR home has a leakier duct system as a result of the use of foil duct tape and because the ducts are located in a loose-fill insulation. Since 2003 all Energy Star homes in the Pacific Northwest are required to use mastic instead of tape to seal ductwork. The forced air distribution system introduces inefficiencies caused by conduction heat transfer between the ducts and the crawlspace, duct leakage to the crawlspace, and duct leakage induced infiltration. Duct leakage induced infiltration results when supply air duct leakage causes negative pressures within the home relative

to the outdoors. Supply duct leakage has been shown to be a significant contributor to uncontrolled air infiltration that increases with the HVAC operational time. (Palmiter 1992) (Persily 2000, 2003). During the winter heating season, longer HVAC operation time combined with greater stack infiltration result in high air change rates. In homes with leaky ducts and envelopes this can result in significant over ventilation and reduces the need for the continuous mechanical ventilation system to operate. The ZEMH's tighter ducts and building envelope reduce winter periods of *over ventilation* making the HRV an important component to the philosophy "build tight; ventilate right."

Table 1 provides a comparison of supply duct and envelope leakage in ZEMH and ESTAR homes using Duct Blasters™ and Blower Doors™ typically employed to test energy efficient homes. Both the ductwork and envelope are considerably tighter in the ZEMH. The difference in both total duct leakage and duct leakage to outside in the ZEMH show the ducts are tighter and that more air leaked through the ducts goes back into the house instead of the crawlspace.

HRV Operation: HRVs are typically used in cold climates to efficiently supply a steady flow of fresh outdoor air. As stale warm air is expelled, the heat recovery core warms the incoming fresh, colder air before it is distributed throughout the home. The result is a constant supply of fresh air, no unpleasant drafts, and greater home comfort. In addition to heat recovery and improved air quality, the HRV provides necessary ventilation while controlling excess humidity. The HRV in the ZEMH is a Venmar 3000™, which is designed to save energy while ventilating and providing High Efficiency Particulate Air Filters (HEPA) filtration of outside and re-circulated air. The Venmar 3000 has a replaceable HEPA filter and separate pre-filter.

The ZEMH HRV measured flow rates were 33-42 l/s (70-90 ft³/min) of *fresh* outside air and exhausts a comparable amount of *stale* indoor air. The operation of the *balanced* HVR does not cause house depressurization and associated air leakage. Stale exhaust air is drawn through the heat exchanger core. The occupant controls include a normal mode for continuous operation 33 l/s (70 ft³/min) and a higher *boost* mode that can be used by occupants when higher levels of indoor air pollutants are present 42 l/s (90 ft³/min). The occupant controls also include a re-circulation mode where HEPA filtration occurs with no air exhausted or introduced and hence no ventilation. The Venmar HEPA 3000 promotes filtration and associated improved indoor air quality (IAQ), unlike many HRV systems specifically designed solely for heat recovery. The ZEMH HRV provides 66 l/s (140 ft³/min), of re-circulated HEPA filtered air and mixes it with a measured 33 l/s (70 ft³/min) of pre-heated outdoor air for a total of 104 l/s (220 ft³/min) supplied to the home on normal speed. The 104 l/s (220 ft³/min) delivered from the HRV is ducted 9 meters (30 ft) using 20 centimeter (8 in) diameter flexible plastic duct located under the attic foam insulation to a ceiling grill in the bedroom hallway at the other end of the home from the HRV return.

Defrost Mode: To ensure that the HRV does not freeze the HEPA 3000 employs a defrost mode with variable timing depending on the outside temperature. When the outside air temperature is between -5° C and -15° C (23° F and 5° F), a mechanical damper shuts the outside air entering the HRV for six minutes every 30 minutes as the defrost mode. This allows the re-circulation air to warm the core. When the outside temperature

is between -15°C and -27°C (5°F and -17°F), the HRV runs in defrost mode for nine minutes every 30 minutes, and 20 minutes every 30 minutes when the outside temperature is below -27° C (-17°F). (Forest) During 2003-2004, the HEPA 3000 was in defrost mode for about 9 hours.

HRV Distribution Effectiveness: The HRV duct design in the ZEMH is independent of the heat pump ducts and not directly ducted to bedrooms. Connecting the HRV to the heat pump ducts would require the 350 watt heat pump blower fan to operate continuously, causing electricity use of up to 3300 kilowatt-hours (kWh) per year. The ZEMH independent duct design reduces energy use. However, it also reduces spatial mechanical ventilation effectiveness in bedrooms when the heat pump is not operating. Research has shown that spatial ventilation effectiveness is improved as the central forced air heating/cooling system operates more frequently to mix the fresh air from the HRV with the indoor air. (Persily 2000)

Figure 2 shows the percentage runtime as a function of outdoor temperature for both the ZEMH and ESTAR home. As expected the runtime increases as the outdoor temperature gets lower during the heating season and increases as the outdoor temperature get higher during the air-conditioning season. The lower runtime in the ZEMH during heating is because the home is more energy efficient and both homes use identical heat pumps. The higher runtime in the ZEMH during the cooling season is a result of the occupant using the heat pump in air-conditioning mode more often in part due to dust, simplicity, and daytime occupancy. The ESTAR occupant relies more on opening windows at night to provide diurnal cooling, instead of using the heat pump. Both occupants will typically open windows when the outside temperature falls within this temperature range. When the heat pump system runs at night, occupants benefit from greater air distribution to the bedrooms. A Venmar duct accessory product currently under development will integrate both duct systems and allow for HRV fresh air to be supplied to all ducted rooms without requiring the operation of the higher wattage heating/cooling fan. This product will improve spatial ventilation effectiveness, will have no negative impact on heating and cooling systems if it uses the same ductwork, and will reduce fan energy use by not relying on the operation of the air handler blower. Another innovative ventilation control used to improve ventilation effectiveness in many energy efficient site built homes is the Fan Recycler™, which ensures that ventilation and indoor air are mixed by the existing forced air system a minimum set time period every hour, by monitoring the HVAC fan runtime. (Rudd)

HRV Maintenance and Operation: The HEPA filter is recommended to be replaced every year. The pre-filter of the HEPA cartridge, HRV core filters and inside of the HRV should be cleaned every six months. The difference in flow rates between the clean and dirty pre-filter was found to be less than 10%, with the HVR core 6-months old. The occupants were asked to run the HRV continuously and use the boost mode when they desired additional ventilation. The HRV in the ZEMH was operated primarily in normal mode. The boost mode was rarely used. The re-circulation mode eliminates outside air. This mode is intended for use during periods when outdoor pollutants are present. Instead of using the re-circulation mode, the occupants shut the HRV off because of

problems with dust, insects and barbeque smoke, which they associated with the HRV. These issues resulted in the HRV being turned off for extended periods of time during the summer of 2003. Discussions with occupants and resolution of problems resulted in HRV continuous operation in 2004-05.

HRV Efficiency: The tested HRV *net efficiency* is 56% provided by Venmar for the HEPA 3000. The net efficiency varies with outside air temperature and flow rate. While there is no industry approved method or test to evaluate the energy recovery efficiency of multifunction products such as the Venmar HEPA 3000, laboratory testing was conducted using CSA C439-00 C439-00 (Standard Laboratory Methods of Test for Rating the Performance of Heat/Energy-Recovery Ventilators) with some adaptations to take into account the impact of blending indoor air inside the unit. The net efficiency has been evaluated from the gross temperature recovery efficiency (defined as apparent effectiveness in CSA C439) to which several penalties were subtracted: unbalance factor, exhaust air transfer, casing air leakage, casing heat gain/losses, defrost energy (when applicable) and fan energy. (Forest)

The measured power consumption of the HRV blower motor in the ZEMH was 164 watts and 228 watts on normal mode and boost mode, respectively. The manufacturer reports that 85 percent of the heat generated from the motor is transferred to the incoming air downstream of the heat exchanger core with the remaining 15 percent transferred to the exhaust air downstream of the core. The high wattage of the Venmar 3000 blower is a result of the HEPA filtration option. Other small wattage Venmar HRV models such as the Duo 1.2™ do not employ HEPA filters and uses only 68 watts to provide 32 l/s (68 ft³/min) at an 87 percent apparent sensible effectiveness at 0° C, (32° F).

NHRV: The ESTAR home utilized a Panasonic #FV-08Q2 Whisper Ceiling™ whole house exhaust fan. The fan is located in the utility room to provide non-heat recovery ventilation. The fan is designed and controlled to operate continuously. A circuit breaker must be turned off to disable operation. The exhaust flow rate was measured at 37 l/s (78 ft³/min) using a flow grid that measures average velocity. Unlike the HRV, the NHRV fan causes a slight depressurization of the home relative to the outdoors. This depressurization causes outside air to enter the home via air leakage pathways in the thermal envelope and ductwork. The location of these leakage pathways dictates the spatial ventilation effectiveness associated with the NHRV system when the heat pump is not operating. Depressurization from the supply duct leakage and NHRV increases ventilation rates. The NHRV exhaust fan flow rate is added in quadrature to the stack effect because of changes in the vertical neutral pressure location. This results in higher flow rate capacity fan required to provide equal mechanical ventilation as the balanced HRV system. For the balanced HRV, the flow rate and stack effect are simply additive.

Energy Gauge USA Simulation: Energy Gauge USA version 2.4 was used to estimate the space heating, cooling and ventilation fan energy for the ZEMH and ESTAR homes as shown in Table 2a. Table 2b compares energy use for a variety of real and theoretical cases. All ventilation cases assume 33 l/s (70 ft³/min). The difference between runs No.1 to No.2 in ZEMH and No.5 to No.6 in ESTAR show the energy savings associated with

not using the HEPA option when using an HRV. The difference between runs No.2 to No.3 in the ZEMH and No.6 to No.7 in ESTAR show the energy savings associated with the HRV over the NHRV. The difference between the Non-ventilation Case 8 over the other ventilation cases highlights the cost of ventilation to achieve improved IAQ. The ventilation system case comparisons in Table 2b indicate greater savings for the ESTAR home than the ZEMH. This is believed to be a result of ZEMH having both lower house and heat pump balance points.

Costs: The HEPA 3000 costs \$1,100 U.S., Duo 2 costs \$700 U.S. and the NHRV costs \$150 U.S. These are costs of the equipment and do not reflect installation, and markups. The HEPA 3000 has a \$100 U.S. annual maintenance cost to replace the HEPA filter. The other units have no annual maintenance costs; cleaning maintenance is assumed to be provided by the occupants at no cost. The useful life of these systems is unknown. It should also be noted that the HEPA filtration non-energy benefits to indoor air quality need to be considered when looking at first and operating costs. These benefits may include the avoidance of health care expenses—such as the cost of a respiratory inhaler and doctor visits—which can far outweigh the cost of energy recovery.

CONCLUSIONS

- HRV systems can improve energy efficiency in new U.S. manufactured housing especially in homes with tighter duct and envelope systems.
- Low fan energy is a factor in HRV and NHRV systems energy performance.
- HRV systems with HEPA filtration require additional fan energy, but provide non-energy related IAQ filtration benefits.
- HRV and NHRV continuous operating systems provide effective ventilation IAQ filtration benefits with varying associated energy costs.
- Controls that reduce over-ventilation are needed especially in homes with leakier ductwork and envelopes (i.e. many non-ESTAR homes).
- Innovative controls and duct components that integrate heating/cooling ductwork with the HRV may improve spatial and temporal ventilation effectiveness.
- Cost analysis alone may not provide “apples-to-apples” comparisons in terms of IAQ benefits.

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Table 1: Duct & Envelope leakage and Ventilation System Flow Rates

Test	ZEMH	ESTAR
Envelope Leakage ¹	2.0 ACH @ 50Pa	3.6 ACH @ 50Pa
Total Duct Leakage ²	145 CFM @ 25Pa (68 L/s @ 25PA) 15% of HVAC flow	211 CFM @ 25Pa (100 L/s @ 25PA) 20% of HVAC flow
Duct Leakage to Outside ²	37 CFM @ 25Pa (17 L/s @ 25PA) 4% of HVAC flow	150 CFM @ 25Pa (71 L/s @ 25PA) 15% of HVAC flow
Whole House Ventilation	70 CFM (33L/s) ³	78 CFM (37L/s)

¹ Tested per ASTM Standard E779-87

² Measured per ASHRAE Standard 152-2002

³ Measured on low-speed with clean pre filter and 3 month old HEPA filter

Case	Home	Type	Efficiency	Watts	Heat kWh/yr	Cool kWh/yr	Heat+Cool
1	ZEMH	HEPA	56%	164	7124	286	7410
2	ZEMH	DUO	87%	70	5759	236	5995
3	ZEMH	NHRV	0%	20	7730	256	7986
4	ZEMH	NONE	0%	0	5045	204	5249
5	ESTAR	HEPA	56%	164	8523	455	8978
6	ESTAR	DUO	87%	70	7034	394	7428
7	ESTAR	NHRV	0%	20	9310	424	9734
8	ESTAR	NONE	0%	0	6268	358	6626

HEPA filtration Cost:	kWh/yr
HEPA vs. Duo in ZEMH	1415
HEPA vs. Duo in ESTAR	1550
HRV Savings vs. NHRV:	kWh/yr
Duo vs. NHRV in ZEMH	1991
Duo vs. NHRV in ESTAR	2306
Cost of Vent vs. None:	kWh/yr
HEPA vs. None in ZEMH	2161
HEPA vs. None in ESTAR	2352
Duo vs. None in ZEMH	746
Duo vs. None in ESTAR	802
NHRV vs None in ZEMH	2737
NHRV vs None in ESTAR	3108

Figure 1: Cross Section of trunk, riser and crossover ducts

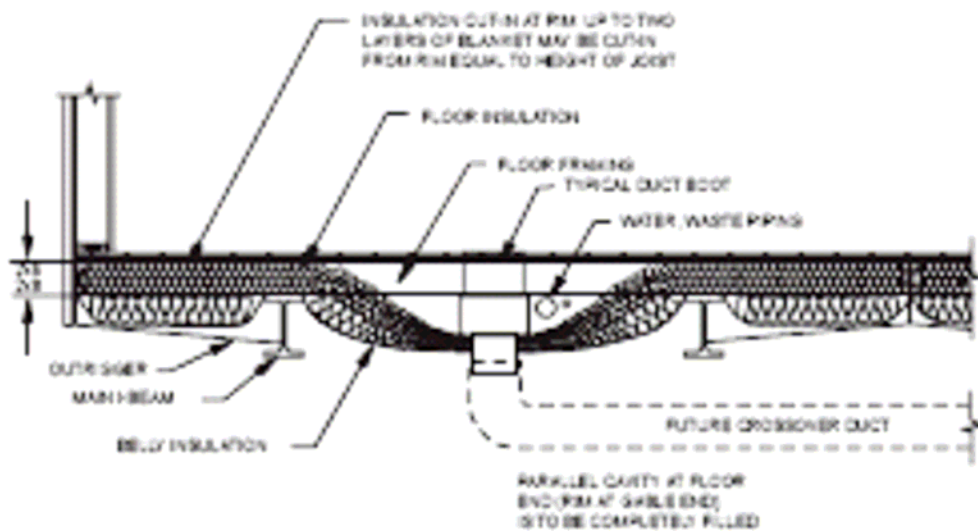


Figure 2: Run time of the ZEMH and ESTAR homes vs. Outside Temperature

