ANALYSIS OF VENTILATION SYSTEMS IN HIGH PERFORMANCE HOMES IN COLD CLIMATES

Christine E. Walker[1] and Douglas Kosar[1]

[1]*Building Sciences Group, Energy Resources Center, University of Illinois at Chicago, Chicago, IL 60607-7054, USA*

ABSTRACT

The performance of three different ventilation systems in cold climate homes is discussed. Comparisons are presented of monitored datasets by contrasting operations of the three ventilation systems, the energy impacts on the overall HVAC systems, and resulting indoor environmental conditions. Whole building simulation results, based on ventilation system models using EnergyGauge® and validated in part by the monitored datasets, provide normalized comparisons of HVAC system energy use. Finally, the economics of the three ventilation system approaches are discussed based on representative installed equipment costs and energy prices, so practitioners from policymakers, code developers, builders, on down to homeowners better understand the first and operating cost tradeoffs.

KEYWORDS

Ventilation systems, monitoring, modeling, residential

INTRODUCTION

Sustained higher heating fuel costs, more energy efficient building codes, and emerging residential ventilation standards are fostering needed research on mechanical means for providing fresh air in cold climate homes to maintain acceptable indoor air quality (IAQ). These more energy efficient homes are adopting construction methods that include applying greater insulation levels throughout the building envelope, along with tighter overall building methods. The combination of these high performance envelopes and tight construction lead to very low air changes per hour (ACH) in residential structures. In order to meet indoor air quality standards, such as those specified by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 62.2-2003 *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*, these homes require the installation of mechanical ventilation systems.

One of three types of ventilation systems was installed in each of three neighboring single-family, detached houses in South Chicago, Illinois, USA. The homes were similarly constructed, using high performance structural insulation panels, and all located within the same housing development. The homes were outfitted with continuous monitoring equipment to record the run-times, inlet and/or outlet air conditions, and energy consumption of mechanical equipment, along with the temperature, relative humidity, and carbon dioxide levels in key areas of the homes. Each house had a blower door test to measure the overall ACH due to natural infiltration. This test not only provided the baseline infiltration for each house, but also ensured that the homes were tightly constructed as designed. Additionally, the individual ventilation systems were tested with flow hoods to measure the actual ventilation airflows.

This paper presents findings for the three ventilation systems that were installed, monitored and modeled for each high performance home. The ventilation systems are described, followed by a discussion of the methodology used in evaluating the monitored data and modeling runs for the ventilation systems. Finally the overall monitoring results for each ventilation system are presented and then compared to the other systems in a normalized manner using the modeled data.

MECHANICAL VENTILATION SYSTEMS

The three ventilation systems were selected based on their respective indoor air quality, initial cost, and operating cost attributes. The three systems evaluated are: 1) Exhaust-Only system, 2) Air-Cycler system, and 3) Energy Recovery Ventilation system. The systems were installed on nearly identical 1728 ft^2 3-bedroom, 2-story homes with basements. Based on ASHRAE Standard 62.2-2003 (ASHRAE 2003), each home required 60 cfm of mechanical ventilation air. Details of each ventilation system are presented below.

Exhaust-Only System

This system uses two bathroom exhaust fans to induce, by design, uncontrolled infiltration through the building envelope which also creates a load on the heating and cooling system of the home. There is no ductwork associated with this ventilation system, which may not distribute air as effectively as the other systems. The fans cycle on and off throughout the day and night, with the fan on for 35 minutes every hour to meet the fresh air requirements via the induced infiltration. The first floor bathroom exhaust fan had a measured flow rate of 59 cubic feet per minute (CFM), while the second floor bathroom exhaust fan had a measured flow rate of 56 CFM. A total energy usage of 45-50 Watts for both fans was measured.

Air-Cycler System

This ventilation system uses a supply-only strategy, introducing outside air when needed to meet fresh air requirements. The air-cycling system is a ducted system that draws outdoor air to the return duct, mixes it with the return air, and then distributes the mixed air throughout the home. A controller operates a damper in the outside air duct that will close if the outdoor air volume requirement has been met. When there are no heating or cooling requirements, the controller will turn on the furnace or AC system supply fan periodically to guarantee that fresh air requirements are met. The air-cycling system used in the test home had a programmable timer used to actuate the outside air damper and initiate supply fan operation, as needed. The timer was set to turn on for 15 minutes and then remain off for 5 minutes, resulting in a 75% run-time. The air-cycling system had a measured flow rate of 80 CFM with negligible measured energy use for the damper motor.

Energy Recovery Ventilation (ERV) System

The ERV system utilizes an enthalpy exchanger (with two small fans) to exchange both heat and moisture between an incoming fresh air stream and outgoing exhaust air stream. This system, like the air-cycling system, requires ductwork and relies on the heating/cooling system to distribute the fresh air throughout the home. When there are no heating or cooling requirements, the heating/cooling system fan turns on periodically in order to meet fresh air requirements. The preconditioning of incoming fresh air with the ERV saves operating energy for heating and humidifying in the winter, and cooling and dehumidifying in the summer. The ERV controller cycled on 75 percent of the time, or 45 minutes per hour. The ERV supply air was measured at 80 CFM, while the exhaust was measured at 54 CFM. This difference was caused by the pressure drop across the filters. The ERV consumed an additional 102 Watts over the 700-800 Watts consumed by the heating/cooling system fan.

METHODOLOGY

Both building monitoring and whole-building simulation was used in evaluating the operation of the ventilation systems. Building monitoring provided data that could then be used in validating the building simulation model. These methods are seen as complimentary; validating energy consumption and performance data with each other. In this section an overview of both the monitoring procedure and building simulation method are presented.

Long-Term Remote Monitoring

The three homes were outfitted with monitoring equipment to ascertain the overall performance of each ventilation system, based on the energy used in operation and the resulting indoor environment. The focus of the research was on cold climates, particularly the heating energy consumption of these ventilation systems. The monitoring was carried out beginning in October 2004 and finishing in May 2005. A fifteen-minute recording interval was utilized for the long-term monitored data.

Measured data covered indoor air conditions, ventilation system operations, and energy usages. Indoor air quality was evaluated by monitoring temperature, humidity, and carbon dioxide levels at several locations throughout the home. Depending on the ventilation system, several measurements were recorded including the intake or mix air temperature and relative humidity, exhaust air temperature and relative humidity, and intake and exhaust airflow rates. As part of the assessment of the homes, a blower door test was performed to determine the natural leakage of each house. The houses were measured to range from 0.04-0.06 ACH, compared to the U.S. Department of Energy (DOE) Building America Benchmark of 0.65 ACH. The overall energy consumption of the homes was measured along with several one-time energy usage measurements already noted. In addition, the furnace/AC fan on-time was monitored. It was not feasible however, to separate out fan calls for heating or cooling from requirements for outside air only within those 15 minute interval datasets.

Whole Building Modeling

To obtain a normalized annual performance, the EnergyGauge® computer simulation (FSEC 2005) was used to model the homes and their different ventilation systems. This software has an easy-to-use graphic user interface over the DOE 2.1E simulation engine and is specifically designed for modeling of residential buildings. The construction specifications and floor plans of the homes were used for the input data to the EnergyGauge® model. Structural insulation panels were specified for the envelope construction, with an R-42.5 rating for the roof and R-24.7 for the walls, and a low infiltration rate based on the measured data. The U.S. DOE Building America Benchmark schedules (Hendron 2005) were used as the input for the lighting, appliance, plug, and water heating loads, which are considered to be the baseline when comparing residential buildings. The building model consisted of a first floor and second floor with an unconditioned basement. The thermostat temperature set point used for all three homes was 76°F for the cooling season and 71°F for the heating season. The actual heating and cooling system capacities and efficiencies of the equipment installed in the homes were used in the building simulations. For heating, the homes had identical 92.5% AFUE high efficiency gas-fired furnaces of 62,780 Btu/hr capacity. Only one of the three homes (the ERV home) was equipped with a 3.5 ton (42,000 Btu/hr), 10 SEER air conditioner, but all homes were modeled with this air conditioner. The supply ventilation for each system was set to 60 CFM for the simulations.

Although this software did contain existing menu selectable options for various mechanical ventilation supply and exhaust systems, it was determined that certain system features such as induced infiltration, furnace/AC fan run-time interlocks, and over-venting damper controls were not yet adequately modeled. So a base case simulation was performed on an unventilated home and then an 8760 hour post-processing spreadsheet analysis of the three ventilation system operations was generated to provide their respective energy usage results.

RESULTS

In evaluating the ventilation systems, annual energy usage and cost was of interest, in addition to meeting indoor air quality standards. First the operation of each ventilation system had to be determined to understand what percentage of time during any hour the ventilation system operated, especially those times independent of the thermostat. Then the internal environments for the homes were compared, followed by the normalized simulation results.

Monitored Home Data

The monitored data for the ventilation systems was separated into monthly datasets, and the run-time fraction of the furnace fan separated into 0.1, or 10% increments. The furnace operating between 70 and 80 percent of a given fifteen minute interval would appear above the '0.8>F>=0.7' label in the figures. This provided a preliminary estimate of the operation of each ventilation system, thereby allowing the comparison of their control strategies. The pattern and number of run-time hours for each system is indicative of the fan energy requirements of each system, as well.

The Air-Cycler System is on for fifteen minutes and then off for 5 minutes for fresh air requirements, resulting in most of the datasets falling above a 60% run-time. The ERV system operates 45 minutes on and 15 minutes off per hour. Much of the data for the ERV is at 100% run-time. The Exhaust-Only system on the other hand operates for 35 minutes each hour, but its operation is not interlocked with the furnace fan, so there are periods of time when it is not in operation, represented by high number of furnace run-time hours of zero (Furnace=0).

The December data is presented in Figure 1, with the ERV system operating at full operation (F=1) over the fifteen minute interval for the most number of hours. In April, when there is a reduced heating requirement, the ERV and Air-Cycler systems operate a reduced number of hours at full operation, but still much more often than the Exhaust-Only system, as seen in Figure 2. The average carbon dioxide level was determined using the measured carbon dioxide levels from the three areas within each home -- the first floor, master bedroom, and second bedroom. The average outside carbon dioxide level, 409 ppm, was subtracted from this average interior level, providing some measure of the indoor air quality. Table 1 presents the number of hours that this difference in carbon dioxide levels exceeded 700 ppm for the 4728 hours of the monitoring period mid October 2004 through May 2005.

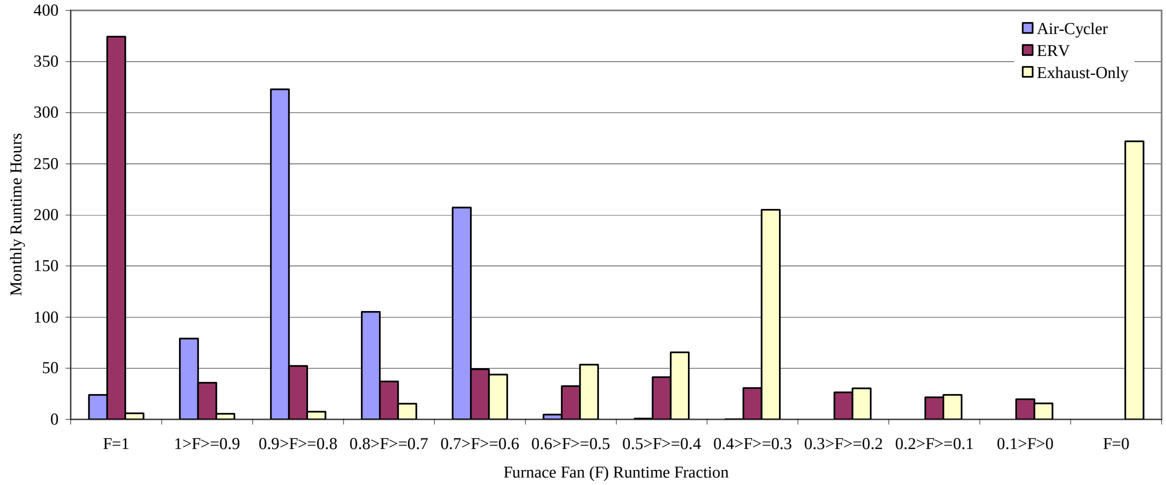

Figure 1: December Monthly Run-Time Hours for the Three Ventilation Systems

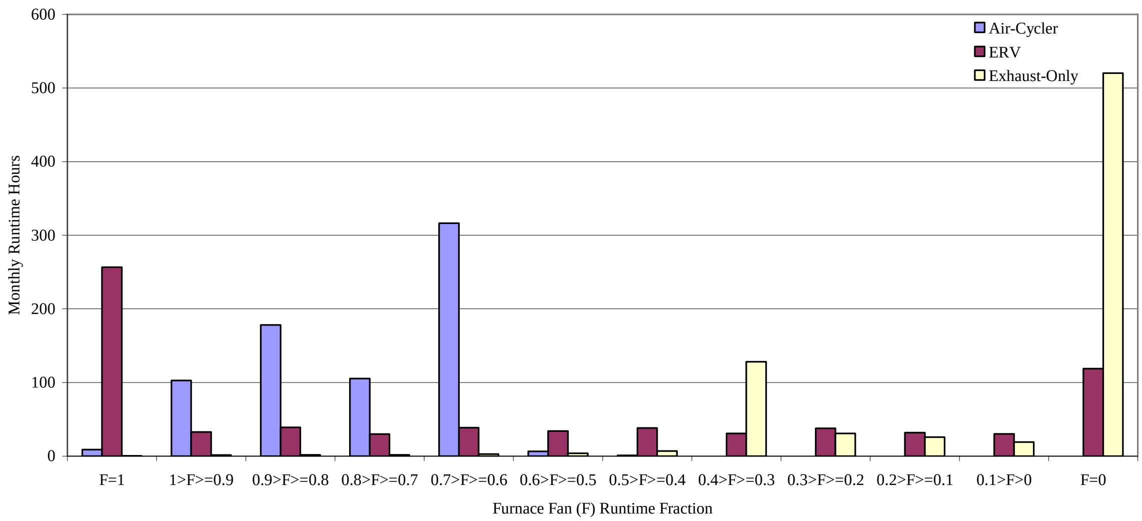

Figure 2: April Monthly Run-Time Hours for the Three Ventilation Systems

EnergyGauge® Simulations

The EnergyGauge® simulations and post-processing spreadsheet analysis allowed a normalized operation of the ventilation systems. The homes were modeled with the same building orientation, temperature set points, internal loads, etc. This provided a direct comparison of the home energy consumption based purely on differences in their ventilation systems. The simulation results for the energy required to condition the home for the three ventilation cases are presented in Table 1. Also included is a base case that represents the high performance home without any ventilation system, providing an additional energy baseline but unacceptable indoor air quality. The heating or cooling energy is the thermal and electrical energy required to condition the supply air. The heating or cooling fan energy is the electrical energy required to distribute the supply air. The ERV system clearly saves heating and cooling energy, but the fan energy associated with exhausting or ventilating air was the significant factor. This was especially true for the interlocking operation with the furnace/AC fan of the Air-Cycler and ERV systems that resulted in substantial supply fan energy requirements solely for ventilation. These operating results are similar to those determined in a companion study by Steven Winter Associates (Aldrich 2005).

TABLE 1

EnergyGauge® Simulation Annual Energy Usage

Energy End Use	*Base Case*	*Exhaust-Only*	*Air Cycler*	*ERV*
Heating (62.78 kBtu/hr) --therms	497	634	634	536
Supply Fan Heating -- kWh	406	524	524	441
Cooling (42 kBtu/hr) -- kWh	1247	1323	1323	1269
Supply Fan Cooling -- kWh	229	244	244	234
Exhaust Fan -- kWh	---	210	---	---
Supply Fan Ventilating -- kWh	---	---	3440	3532
ERV Fan -- kWh	---	---	---	670
Total -- kWh	1881	2302	5531	6147
Total -- therms	497	634	634	536
Annual Energy Cost -- $/yr at $0.60/therm and $0.10/kWh	$486	$611	$934	$936
System Installed Cost Premium ($)		$230	$300	$1200
Air Quality(monitored data Oct'04–May '05) Number of Hours CO2 Levels above 700ppm	unacceptable	138	124	314

SUMMARY

Through monitoring and simulation of alternative ventilation systems, a better understanding was attained regarding their operating characteristics and energy implications. The systems were designed to meet minimum indoor air quality requirements, as set by ASHRAE Standard 62.2, and then the energy consumption associated with the operation of these ventilation systems was assessed. The interlock of the Air-Cycler and ERV systems with the supply fan, to meet minimum run-times for indoor air ventilation requirements in addition to heating/cooling requirements, caused substantial energy consumption increases, made worse when furnace/AC systems were oversized and already had short run-times. The energy usage for the Exhaust-Only system was substantially lower than the other two systems, as it only required a 50 Watt power draw, as opposed to the 750 Watt interlocked furnace fan power draw. The Exhaust-Only system is also projected to have the lowest installed cost premium of the three systems as well, if a single exhaust fan and controller can be used as priced in Table 1.

ACKNOWLEDGEMENTS

The authors would like to thank the National Center for Energy Management and Building Technologies and the Department of Energy for their financial support of this research and Steven Winters Associates for sharing their monitored home data and providing technical assistance with the data analysis.

References

Aldrich, R. (2005) Research and Ideas: Furnace Fan Penalty. Energy Design Update. Aspen Publishers. **25:6**. June 2005.

ASHRAE Standard 62.2 (2003) *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, USA.

Florida Solar Energy Center (2005), EnergyGauge® USA Residential, A Residential Energy Design Software, Cocoa, FL, USA, www.energygauge.com/USARes/default.htm .

Hendron, R. (2005). Building America Research Benchmark Definition, Updated December 29, 2004, National Renewable Energy Laboratory, Golden, CO, USA.