Residential Air Infiltration and Ventilation Study in New York State

Peter Strunk, Synertech Systems Corporation
Laurence F. Kinney, Ph.D., Synertech Systems Corporation, E Source, Inc.
Robert M. Carver, P.E., New York State Energy Research and Development Authority

ABSTRACT

This paper summarizes an evaluation of four types of continuous-capable mechanical ventilation systems installed at eight homes in upstate New York. Continuous-capable systems are able to provide full ventilation rates at all times without assistance from natural ventilation. Measurements of air exchange, airflows, pressure differences, and electrical power consumption were made to assess the systems' performance. Design and installation practices, as well as installation costs, were also evaluated. Seven of the eight installed ventilation approaches made a measurable improvement in their homes' ventilation rates. When continuously operated, five of the eight approaches increased their homes' ventilation rates to a level that met or exceeded recommended American Society of Heating, Refrigerating, and Air-conditioning Engineers' guidelines. The estimated annual heating and cooling cost increase when the ventilation systems were operated continuously ranged from $65 for heat-recovery units to $300 for outside air-duct systems that relied on furnace fans for distribution. The installation costs ranged from $1,500 for simple exhaust-only systems to $3,500 for stand-alone heat-recovery systems, excluding contractor profit.

Introduction

Residential ventilation systems are becoming more important as efforts to reduce space-conditioning energy costs in homes' lead to tighter building envelopes, both in new construction and in existing weatherized houses. Tight envelopes can cause insufficient natural air exchange with the outdoors. In cases where moisture and other indoor pollutants are generated faster than natural air exchange can dilute or remove them, the occupants or structure may suffer if additional mechanical ventilation is not provided.

In response to this problem, American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) Standard 62, Ventilation for Acceptable Indoor Air Quality, recommends minimum installed outdoor air supply capacities for homes according to occupiable floor area and number of bedrooms. In addition, minimum bathroom and kitchen exhaust rates are offered. These rates are intended to be available upon demand at any time; thus the recommendations can only be achieved if mechanical ventilation is capable of providing the full rate(s), with no help from natural ventilation. This project evaluated the performance associated with continuous-capable ventilation systems in eight houses to determine compliance with Standard 62; installation and operating costs were also estimated.

This paper summarizes a comprehensive project report prepared by Synertech Systems

Corporation for the New York State Energy Research and Development Authority (NYSERDA). This project was funded by NYSERDA as part of a two-phased program to evaluate ventilation options for New York State homes.

Demonstration Sites and Systems

Eight houses were included in this study as demonstration sites. The eight evaluation homes were located in New York State, less than 20 years old, and less than 1,900 square feet of living area in five cases. All were tighter than 7.0 air changes per hour (ACH) at 50 Pascals (ACH50), a common building envelope leakage threshold below which mechanical ventilation is recommended. The individual characteristics of the eight homes are summarized in Table 1.

One of four different types of ventilation systems was installed in each of the eight homes. These systems were as follows.

Stand-alone Heat or Energy Recovery Ventilator (HRV/ERV). In a stand-alone HRV or ERV system, supply and exhaust fans are contained in the HRV/ERV cabinet. A small exhaust duct system brings stale air from the house to the HRV/ERV, while a small-supply duct system delivers fresh air to the house from the HRV/ERV. There are two other short ducts - one fresh air and one stale air - that connect the HRV or ERV to the outside.

The two air streams pass through a heat or energy exchange core or medium inside the cabinet, allowing the incoming fresh air to be tempered by the outgoing exhaust air. In addition to alleviating fresh air grille comfort problems in the living space, this exchange of heat or energy can reduce the space heating energy required during ventilation.

Integrated HRV/ERV System. In an integrated HRV or ERV system, a short duct delivers fresh air from an HRV or ERV into the return trunk of a warm-air heating system, rather than directly to the living space. Because the HRV/ERV warms the fresh air before it is delivered to the return ductwork, the furnace fan does not have to run with the HRV or ERV for comfort. This warming also prevents excessively cooling a furnace heat exchanger on cold days, which could cause the heater exchanger to crack due to thermal stresses when the furnace fires up.

An integrated system may also remove exhaust air from the return side of a warm-air heating system through a second short duct connected to the HRV or ERV. In this case there are no living space grilles at all, for either supply or exhaust. An integrated system that only supplies fresh air to a warm-air heating system is referred to here as a one-connection system, while an integrated system that also removes exhaust air from the heating system is called a two-connection system. It is important to have good distance between the connection points for a two-connection system, and a damper or filter between connections may be necessary. This distance is suggested to prevent fresh air flow short-circuits within the warm-air system (e.g., moving from the HRV supply connection directly to the HRV exhaust connection).

Table 1. Overview of the Eight Houses and Ventilation Systems

Criteria / House ID	1	2	3	4	5	6	7	8
Built in	1988	1992	1989	1994	1997	1996	1994	1991
Living area (sq ft)	1,068	1,610	2,074	2,839	1,389	2,452	1,158	1,802
Conditioned Volume (cu ft)	8,540	12,765	16,770	23,954	11,110	19,879	9,265	14,414
Foundation Type	basement	basement	basement	basement	basement	basement	basement	basement
Heating system type	warm-air	warm-air	warm-air	warm-air	hydronic	hydronic	hydronic	hydronic
Heating Fuel	gas	propane	gas	propane	oil	oil	oil	oil
Heating equipment input (Btu/hr)	45,000	100,000	95,000	75,000	98,000	138,000	103,500	82,800
Ventilation system type	mixing 2 speeds	integrated HRV 3 speeds	mixing 1 speed	integrated HRV 5 speeds	HRV 2 speeds	HRV 3 speeds	exhaust w/4 inlets 2 speeds	exhaust w/o inlets 1 speed
Fresh air delivered to	warm-air return trunk	warm-air return trunk	warm-air return trunk	warm-air return trunk	bedrooms (3)	bedrooms (2), TV room, family room	bedrooms (3), living room, rooms with envelope leaks	rooms with envelope leaks

Mixing System. In a mixing, or outdoor air duct, system the warm-air furnace fan acts as a supply fan by pulling fresh air into the return trunk through an outside air duct. A separate exhaust fan removes stale air from the house at the same time. The furnace fan, the exhaust fan, and a powered damper in the outside air duct are all connected to the ventilation controls so that they run together. Inside the duct system the recirculating room air mixes with the cold outside air, warming it to prevent comfort problems and to prevent potentially hazardous cooling of the furnace heat exchanger when the burner is off. The fresh air is delivered along with the recirculating house air to each warm-air supply register.

Exhaust-only System. An exhaust-only system provides supply air by increasing building leak infiltration during operation of an exhaust fan. The increased infiltration air does not cause comfort problems if there are no large building leaks. Exhaust-only systems may also include intentional air inlets to provide fresh air during fan operation. Air inlets are mounted high on a wall, and direct incoming air upward, giving it time to warm before falling into the occupant zone.

Although all of the systems installed are capable of continuous operation, occupants are able to control the actual run-time according to their needs. A common schedule during the project included continuous operation when people were home in the morning and evening. Seven of eight systems use a 24-hour programmable timer to control operation, while one of the recovery systems uses a control offered by the manufacturer.

For each individual home, Standard 62 was used to determine both the design fresh air supply rate for the whole house and the design exhaust rates for individual bathrooms and the kitchen. Where possible, advanced ventilation goals were met during design, such as directing fresh air predominately to the bedrooms, which are often occupied with the doors closed, and installing exhaust and supply air grilles near the top of a room instead of nearer the floor. Air-moving equipment (fans, HRVs) and ducting was selected to deliver the recommended airflows for each house, according to the equal friction duct design procedure given in 1996 ASHRAE HVAC Systems and Equipment.

Testing Methods and Results

Diagnostic tests were conducted at each home to assess the installed systems' performance. These tests included measurements of building leakage, warm-air system duct leakage and airflows, ventilation system airflows and noise and power levels, and air exchange under different conditions. House pressures were also measured to identify potentially hazardous basement depressurization situations.

In addition, temperatures and equipment operation were monitored for two 10-day periods at each house, the first with only intermittent bathroom and kitchen ventilation, and the second also including operation of the new system for a set fraction of each day determined by the homeowner.

Diagnostic testing included short-term measurements of air exchange using either sulfur hexafluoride (SF6) or carbon dioxide (CO2) in a tracer gas decay method for different combinations of equipment operation. Nearly every individual decay sequence was conducted according to ASTM Standard E741-95, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. During testing at houses 1, 4, and 8, individual zone gas concentrations deviated from the average concentration by more than 10%, which is the E741-stipulated maximum for application of the error analysis. In these cases the short-term test results may indicate useful trends, but the other types of diagnostic tests may represent the systems more conclusively.

The results of the short term air exchange tests for the whole house and master bedroom are given in Table 2.

At these eight houses, the ventilation systems added an average of 0.23 ACH to the whole house ventilation rate, and an average of 0.41 ACH to the master bedroom rate. A short analysis of the whole house air exchange measurement error was conducted. This analysis determined that seven of the eight installed ventilation approaches made a measurable improvement in their home's air exchange rate. This analysis suggested the change in air exchange rate in House 4 was within the range of measurement error, suggesting that a substantial change in the air exchange rate did not occur because of operation of the ventilation system in this house.

Table 2. Whole House and Master Bedroom Air Exchange Rates During High Speed Continuous Operation

	Air Changes Per Hour			
	Ventilation Off		Ventilation On	
ID	Whole House	Master Bedroom	Whole House	Master Bedroom
1	0.14^{A}	0.25^{A}	0.3	0.61
2	0.17	0.03	0.39	0.15
3^{B}	0.10^{A}	0.10^{A}	0.22	0.17
4	0.47	0.4	0.66	1.59
5	0.26	0.13	0.55	0.88
6	0.07	0.11	0.56	0.46
7	0.07	0.05	0.32	0.25
8	0.29	0.17	0.42	0.39

^{A}Furnace fan on ^{B}Bedroom 2 instead of Master BR

Air exchange was also measured for two longer periods at each house, generally between 10 and 14 days in length, using Brookhaven National Laboratory's Air Infiltration Measurement System (AIMS) perfluorocarbon tracer source/passive sampler method. The first AIMS period at each house included intermittent bath and kitchen ventilation only, while the second also included operation of the continuous ventilation system on a programmed schedule. Electronic monitoring of weather and equipment operation was conducted during the AIMS periods to record conditions.

Table 3 provides the whole-house and bedroom zone AIMS results for all eight houses, as well as the fractional run-time of the ventilation systems during the semi-continuous periods.

The measured air exchange values from these tests are necessarily limited to the environmental conditions in place during the testing. However, average inside-outside temperature difference and wind speed values for each AIMS and short-term test period were collected to allow some assessment of the similarity of environmental conditions between the two periods. If average conditions are similar, measured differences in air exchange caused by the new ventilation system may be informative, for those conditions. This allows some assessment of the incremental changes in air exchange caused by these ventilation systems under the test conditions.

Table 3. AIMS Measurements of Whole House and Master Bedroom Air Exchange Rates

ID	Air Changes Per Hour						Semi-Continuous Fractional Run-Time
	Whole House			Bedroom Zone			
	Intermittent Ventilation Only	Semi-Continuous Ventilation	Change	Intermittent Ventilation Only	Semi-Continuous Ventilation	Change	
1	0.201	0.217	0.02	0.155	0.21	0.06	0.27
2	0.209	0.274	0.07	0.296	0.153	-0.14	0.21
3	0.26	0.24	0.02	0.271	0.229	-0.043	0.31
4	0.268	0.275	0.007	0.936	0.896	-0.04	0.76
5	0.309	0.436	0.127	0.166	0.485	0.319	0.45
6	0.157	0.211	0.05	0.366	0.508	0.142	0.63
7	0.15	0.18	0.03	0.004	-0.023	-0.027	0.29
8	0.296	0.344	0.05	0.206	0.209	0.003	0.41

Similar weather conditions between the AIMS intermittent and semi-continuous tests were observed for all houses except 1, 2, and 8. At these houses, inside-outside temperature differences for the semi-continuous tests were smaller than for the intermittent tests. This occurrence suggests that the natural infiltration forces on these houses during the semi-continuous tests were not as great as during the intermittent tests. It is reasonable to assume that air exchange in these houses would have been higher during the semi-continuous tests if weather conditions had been more similar to those observed during the intermittent tests.

Similarly, the short-term ventilation-on and ventilation-off tests at houses 3 and 5 through 8 were conducted under similar weather conditions and often consecutively on the same day. Ventilation-off and ventilation-on tests for houses 1, 2, and 4 were conducted on different days, resulting in inside-outside temperature differences that were not similar between tests. However, in houses 1 and 4, a smaller inside-outside temperature difference was observed during the ventilation-on tests than during the ventilation-off tests, suggesting air exchange in these houses would have been higher during the ventilation-on tests if weather conditions had been more similar to the ventilation-off weather conditions.

Energy Impacts

The energy costs associated with the various levels of ventilation in the eight homes were estimated using a spreadsheet model, both for the fractional run-times, or duty cycles, observed during the monitoring, and for duty cycles equal to one (continuous operation). The spreadsheet model extrapolated experimental data to produce normalized results for space conditioning seasons in New York (6,100 heating degree days and 800 cooling degree days.)

The energy costs include (1) space-heating or space-cooling energy required to condition the additional outside air, and (2) electricity to run the space-heating or space-cooling distribution fan or pump(s), as well as the ventilation equipment. In the case of cooling, space conditioning energy is in the form of electricity as well. Average energy prices for New York State used in the spreadsheet model were $0.12/kWh for electricity, $6.77/Mbtu for gas, $10.48/Mbtu for propane, and $5.72Mbtu for oil. These energy prices were based on estimates provided by the New York State Public Service Commission.

The heating results are shown in Figures 1 and 2, while the cooling results are shown in Figures 3 and 4. The energy impacts shown for intermittent operations are for the duty cycles observed during the monitoring periods.

The total annual cost of ventilation at these eight homes, in extra heating energy, cooling energy and electricity usage is estimated to be as low as $64 and as high as $303 for continuous operation. The annual costs on a square foot (sqft) basis for continuous operation ranged from $0.05/sqft to $0.23/sqft. Mixing systems, which require furnace fans to run during ventilation operation, cost the most to operate ($0.15/sqft to $0.23/sqft). Using the actual fractional ventilation run-times that were monitored during the project - and which generated favorable homeowner comments regarding indoor air quality - annual costs were between $20 and $92. The annual costs on a square foot basis for fractional ventilation run-times ranged from $0.01/sqft to $0.05/sqft. All eight systems are estimated to cost less than $70 per heating season and less than $40 per cooling season under the monitored fractional duty cycle conditions. The annual costs on a square foot basis for fractional ventilation run-times were all less than $0.03/sqft for heating and less than $0.02/sqft for cooling.

Further, only the two mixing systems required more than $250 for the combined heating and cooling season when running continuously. These costs are perhaps modest prices to pay for potentially better indoor air quality and wintertime comfort.

Installation Issues and Costs

Stand-alone HRV/ERV systems are in general considered the best-performing type of ventilation system. Extensive ducting can allow the total exhaust flow to be concentrated in bathrooms and the kitchen, and total supply flow can be concentrated in the bedrooms and other frequently occupied rooms. Both stand-alone HRV/ERV systems used here achieved good whole-house air exchange rates and good air exchange rates in the rooms with fresh air grilles. These two systems were the most expensive of the eight in both materials and labor because of the extensive ducting and expensive air-moving equipment, especially in the larger ERV home. Total costs were $2,608 for the HRV home and $3,554 for the ERV home.

Where a stand-alone HRV/ERV system is too difficult or expensive to install, such as in retrofit situations, integrated HRV/ERV systems that use warm-air ducts as the fresh air distribution network still offer heat or energy recovery. To limit noise, the furnace fan ideally does not run for ventilation. Both of the integrated HRV systems used here were retrofits, with one connected to the warm-air ducts to distribute fresh air only and the second connected to remove exhaust air from the warm-air ducts as well.

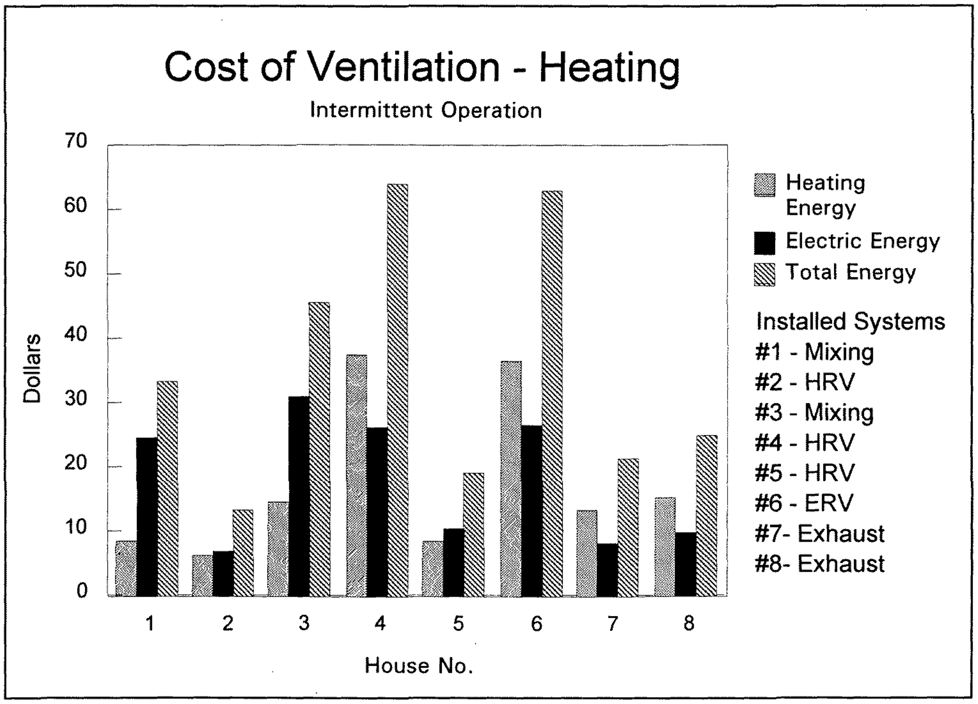

Figure 1. Cost of Ventilation During the Heating Season, Monitored Duty Cycles

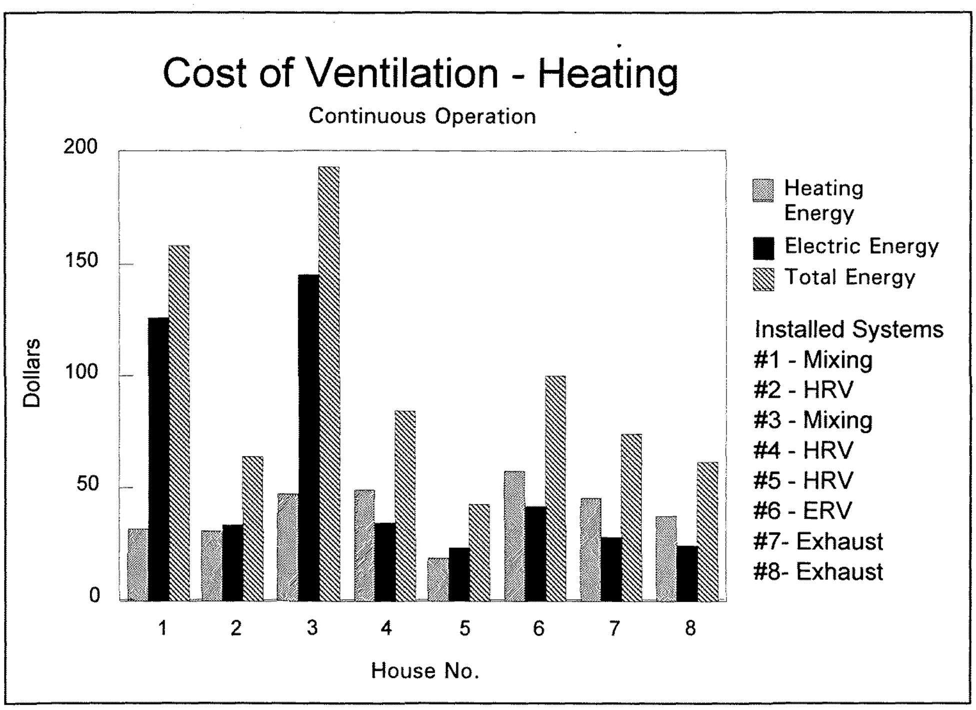

Figure 2. Cost of Ventilation During the Heating Season, Continuous Duty Cycles

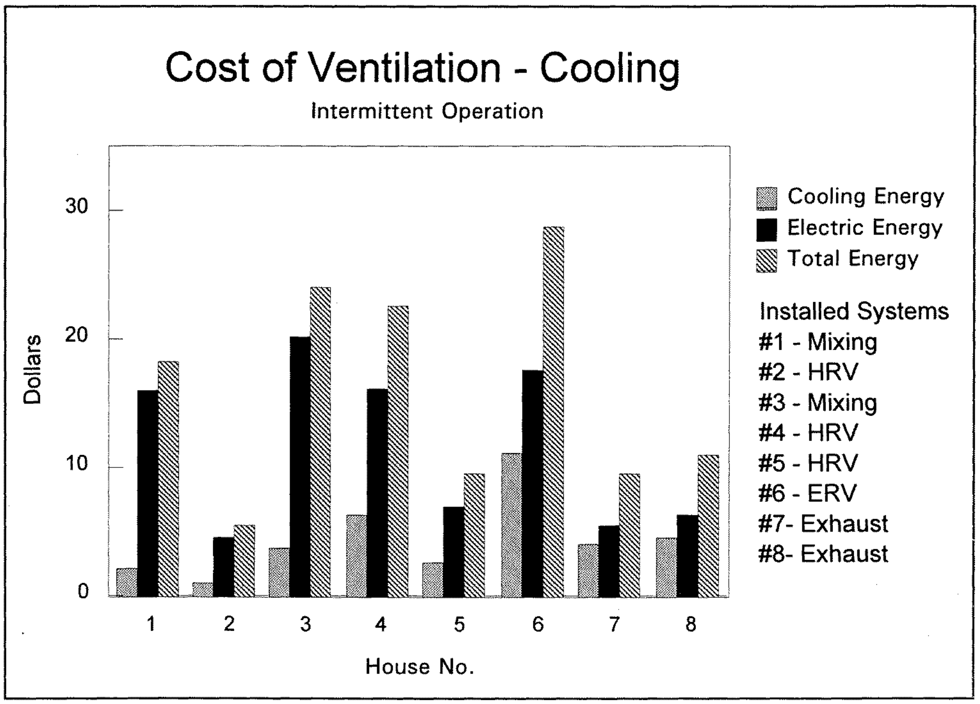

Figure 3. Cost of Ventilation During the Cooling Season, Monitored Duty Cycles

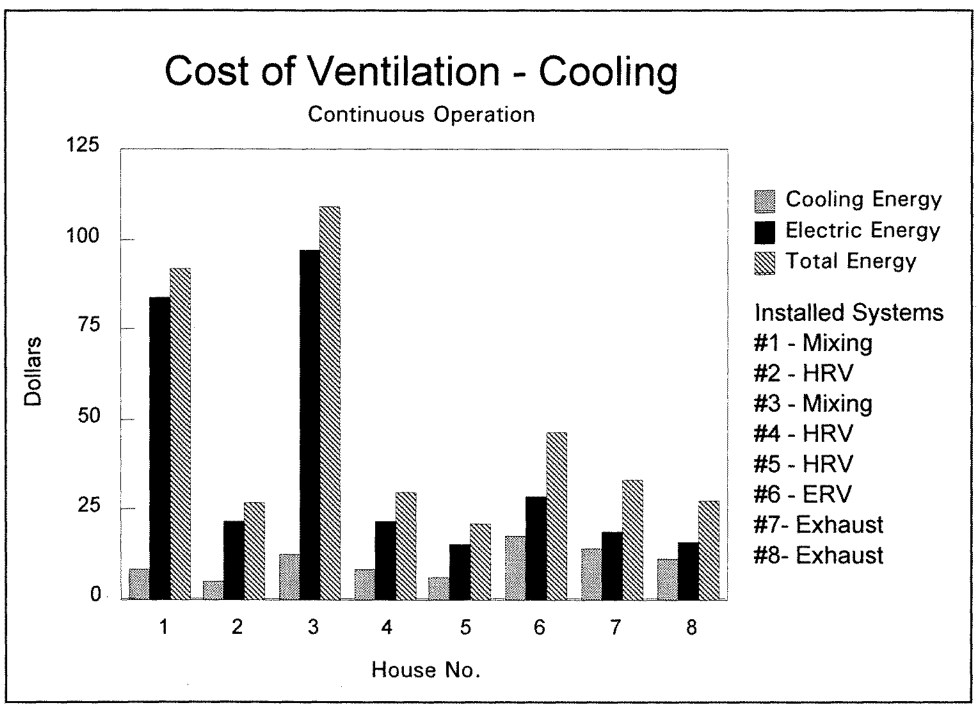

Figure 4. Cost of Ventilation During the Cooling Season, Continuous Duty Cycles

Both integrated HRV/ERV systems were found to fall slightly short in achieving the expected increases in whole-house air exchange, and counterproductive effects were observed in each house. However, system airflows were close to design values. The two-connection system was the least expensive of the eight in labor, and least expensive of the four HRV/ERV systems in total cost at $1,835. The total cost for the one-connection system was $2,490.

In the two-connection house, despite the significant distance between the two connection points, almost 50% of the total fresh air flow short-circuits within the warm-air system, moving from the HRV supply connection directly to the HRV exhaust connection. Short-circuiting in this best-case situation means that such a two-connection arrangement will short-circuit in most other houses. A simple barometric damper, or perhaps a high-resistance pleated filter, must be installed between the two warm-air return connection points to prevent short-circuiting. This approach calls for a lightweight slide-in unit that does not require disassembly of the return trunk. The cost of this necessary component and the labor to cut a slot and screw the damper in place may be approximately $100.

In the one-connection house, fresh air was found to be concentrated so heavily in the bedrooms during ventilation that the whole-house rate did not show the desired improvement. This situation illustrated the importance of the relative locations of the fresh air return trunk connection and the first floor return registers in determining distribution of fresh air.

Mixing systems were one of the two non-recovery system types evaluated. The warm-air systems need to be relatively quiet to be incorporated into mixing systems because the furnace fan runs for ventilation. The occupants did notice cool air near certain registers when it was very cold outside, especially below two ceiling registers in one house. These occupants decided to schedule ventilation for sleeping hours to avoid this comfort problem. Neither of the occupants reported noise from the warm-air system as a problem during ventilation.

Further, the high-speed design flow rate based on house size was not achievable at one of the houses with a mixing system because of very low return duct pressure. The outside air duct for a mixing system should be sized with the actual or expected return trunk pressure in mind.

The two mixing systems cost $2,072 and $1,979, close to the integrated HRV/ERV system costs. The total materials costs were lower than those found for all four HRV/ERV systems but greater than those for the exhaust-only systems.

The two exhaust-only systems - the least expensive of the eight systems - were installed in hydronically-heated homes as retrofits. In both homes, an exhaust fan depressurized the house slightly, which increased total infiltration flow through leaks in the building envelope and, in one house, through intentional air inlets mounted on exterior walls.

One of the exhaust-only systems was installed during construction; the other was a retrofit in an existing home. The new-construction system included a basement-mounted in-line fan serving two bathrooms and an air inlet in each of four rooms, for $1,504, while the existing home received an attic-mounted in-line fan serving only the common bathroom and no inlets, for $1,426. A dedicated make-up air fan for a boiler closet was included in this second system. The exhaust-only systems were very satisfactory to the occupants of both homes, with comments on improved air quality and quiet operation offered in both cases.

Table 4 shows a detailed breakdown of the installation costs associated with the eight ventilation systems. Travel, design labor, and material procurement labor are not included. Materials were obtained from normal contractor suppliers, who typically sold at retail less 10%.

It is important to note that the systems at houses 1, 3, and 8 would probably have been less expensive had they been installed during construction of the homes. All three of these homes required extensive attic work, which is more time-consuming in an occupied house. House 8 also required a make-up air unit for the existing boiler. A new home like number 8 that included a sealed-combustion boiler would not require a make-up air unit, saving $189 plus six hours of labor.

Table 4. Installation Costs

		Material Costs: retail less 10% (US $)					Labor		
ID	System Type	Fan or HRV or ERV[A]	Controls and Wiring	Ducts	Hoods and Grilles	Total Mtls.	Hrs	Cost $35/hr (US $)	Total Cost (US $)
1	Mixing	141	332	136	28	637	41	1435	2072
2	Int. HRV	794	46	112	43	995	24	840	1835
3	Mixing	141	325	85	28	579	40	1400	1979
4	Int. HRV	874	66	97	53	1090	40	1400	2490
5	SA HRV	734	82	192	95	1103	43	1505	2608
6	SA HRV	1185	113	482	59	1839	49	1715	3554
7	Exhaust	321[B]	66	56	11	454	30[C]	1050	1504
8	Exhaust	316	93	94	13	516	26	910	1426

[A] includes mounting hardware, and condensate pumps for HRVs
[B] includes four air inlets
[C] includes estimated 18 hours to install air inlets, exhaust riser duct, and exterior hood, during original construction of house

The total costs in Table 4 represent contractors' costs to install the systems; the consumer would likely pay an additional 20 to 50% in contractor profit and overhead.

Conclusions

The four system types demonstrated in this project seem to fill important niches in the range of design/installation situations that might be encountered. The sample of eight homes in the studied group is small, which means that an individual system type's performance would probably have to be persistently and inexplicably insufficient in order to remove that system type from consideration in New York State. However, the collected data suggests none of the four system types stand out as poor candidates for continued development.

The work at the eight homes demonstrated that these continuous-capable ventilation systems all have the potential to satisfy Standard 62. However, important conditions for success were found, both from design and installation standpoints. The system improvement suggested by this work should be applied and validated at the two-connection integrated HRV house before undertaking additional study of this system type.

Acknowledgments

The primary author wishes to acknowledge the hard work of his coauthor, without whom this project could not have been accomplished. In addition, thanks go out to the other members of the Project Advisory Committee who contributed suggestions along the way: Mike Clarkin, Al DeDominicis, Helmet Feustel, Mimi Goldberg, Bob Kelley, Nance Matson, Andrew Persily, and Joe Rizzuto. Russell Dietz at Brookhaven National Laboratory was also invaluable in the completion of this project

References

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 1996. *1996 ASHRAE Handbook - Heating, Ventilating and Air-Conditioning Systems and Equipment.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 1990 *ASHRAE Standard 62-1989 Ventilation for Acceptable Indoor Air Quality.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers

American Society for Testing and Materials, 1995, *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution (E741-95).* Conshohocken, PA: American Society for Testing and Materials

Dietz, Russell N. 1989. *Brookhaven Air Infiltration Measurement System.* Upton NY: Brookhaven National Laboratory.

New York State Energy Research and Development Authority and Synertech Systems Corporations, 1999, *Air Infiltration and Ventilation Project.* Albany, NY: New York State Energy Research and Development Authority.