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Effect of Control Strategies on Ventilation System Performance

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Synopsis

Dynamic computer simulations were used to compare residential ventilation methods to identify an approach that would improve indoor air quality with minimum energy penalty while maintaining comfort. Various ventilation methods and control strategies were evaluated to determine the cost of providing the ASHRAE-recommended minimum ventilation level of 0.35 air changes per hour (ach).

Analysis of simple ventilation methods showed that single-direction ventilation partially compensates for high natural infiltration levels and saves about half the energy cost of ventilating with a two-direction method without heat recovery. Of the single-direction ventilation methods considered, the strategy of continuous exhaust fan operation to provide 0.35-ach mechanical ventilation did not result in the lowest annual energy cost. Other single-direction ventilation methods, such as connecting an outdoor air duct to the return plenum, had relatively low annual energy costs. In tightly constructed homes with few cracks through which a single-direction fan could force air, two-direction ventilation may be required. Simulations indicate that a heat recovery ventilator significantly reduces the annual energy cost of two-directional ventilation.

Simulations showed that if the amount of natural infiltration is known exactly, a significant energy cost savings is possible compared to the constant two-direction ventilation without heat recovery.

Keywords: *air leakage, air quality, comfort, consumption, control, energy, residential, total energy, ventilation*

Introduction

Growing concerns over indoor air quality have resulted in a need to define and compare residential ventilation methods and applicable control strategies. The objective of this study was to use dynamic simulation models to analyze residential ventilation control strategies that provide air quality benefit with minimum energy penalty while maintaining comfort. Various ventilation methods and control strategies were evaluated to determine the cost of maintaining the ASHRAE-recommended 0.35-ach minimum ventilation level (ASHRAE Standard 62-1989). Simulations for both the heating and cooling seasons with a heat recovery ventilator (HRV) and several other ventilation methods were conducted using the Generalized Engineering Modeling and Simulation (GEMS) program [Benton et al., 1982]. The ventilation methods considered were evaluated based on initial cost, operating cost, comfort, and ability to maintain the ASHRAE-recommended 0.35 ach. Results obtained thus far are for a single house model and a single location:

- Two-story house with basement
- Reasonably tight envelope (annual average infiltration of 0.33 ach)
- Furnace fan draws make-up air into return duct whenever fan is on (approximately the same amount as the stack flow)
- Exhaust fans available but not automatically used during cooking or showering
- Heat recovery ventilator available for ventilation
- Minneapolis weather data
- Energy costs for Minneapolis (gas: $0.50/therm; electric: $0.06 /kWh)

Layout of the simulated house, construction, and HVAC system was based on an actual house located in Eden Prairie, Minnesota, which has been used in the past for field testing prototype controllers. The only paths for air to flow between the inside and the outside of the house are the furnace stack, the make-up duct, and cracks in the building's structure. Stack flow is calculated as a function of the stack temperature, and make-up air is considered to be a constant value whenever the furnace fan is on and zero when the fan is off. Infiltration was modeled as a function of both wind speed and indoor-to-outdoor temperature difference [*ASHRAE 1997 Fundamentals*]. In this simulated system, the make-up flow equals the nominal stack flow (84 cfm (39.65 L/s)), the furnace fan is on only when required, and no mechanical ventilation is designated as the reference or base case. The decision not to use exhaust fan operation for the base case is consistent with a report in *Environmental International* [1989] stating that only 12% of the homes surveyed were said to truly benefit from vented range fans. In most homes, if a range fan was installed at all, it was not used significantly.

Using Minneapolis weather data, the simulated base ventilation level ranged from less than 0.1 ach to approximately 0.5 ach with an annual energy cost of $680. The difference between the operating cost for this baseline system and any other system intended to provide better ventilation is then the cost of the ventilation method or control strategy under consideration. Heating and cooling season simulations were conducted for five ventilation methods: the base or "no ventilation" case; the case where natural infiltration is assumed to be known exactly and two-direction mechanical ventilation without heat recovery is available to provide the minimum ventilation level; two-direction mechanical ventilation without heat recovery to provide a constant 0.35 ach; two-direction mechanical ventilation with heat recovery to provide 0.35 ach; and constant 0.35-ach single-direction mechanical ventilation. These five cases encompass most of the important conclusions regarding heat recovery, single- versus two-direction ventilation, and the importance of knowing natural infiltration level to ventilate efficiently.

Single- vs. Two-Direction Ventilation

The simulations indicate that for all but supertight homes, single-direction ventilation methods are preferable to two-direction ventilation methods on an economic basis. The reason is that they have a lower peak ventilation rate for the same minimum ventilation rate; that is, single-direction ventilation overventilates less than two-direction ventilation. Figure 1 shows that on a windy day, 140 cfm (66.1 L/s) of single-direction mechanical ventilation results in an increase of only 70 cfm (33.0 L/s) in the total ventilation of the house, whereas on a calm day it still results in 140 cfm (66.1 L/s) of total ventilation. In contrast, two-direction ventilation increases the total ventilation by 140 cfm (66.1 L/s) in both cases, resulting in more overventilation on windy days. The arguments used for windy conditions are also applicable for cases when there is a large indoor-to-outdoor temperature difference.

In tighter structures, the savings associated with single-direction ventilation will be less dramatic, since with little natural infiltration, virtually all of the required 0.35 ach must be provided by

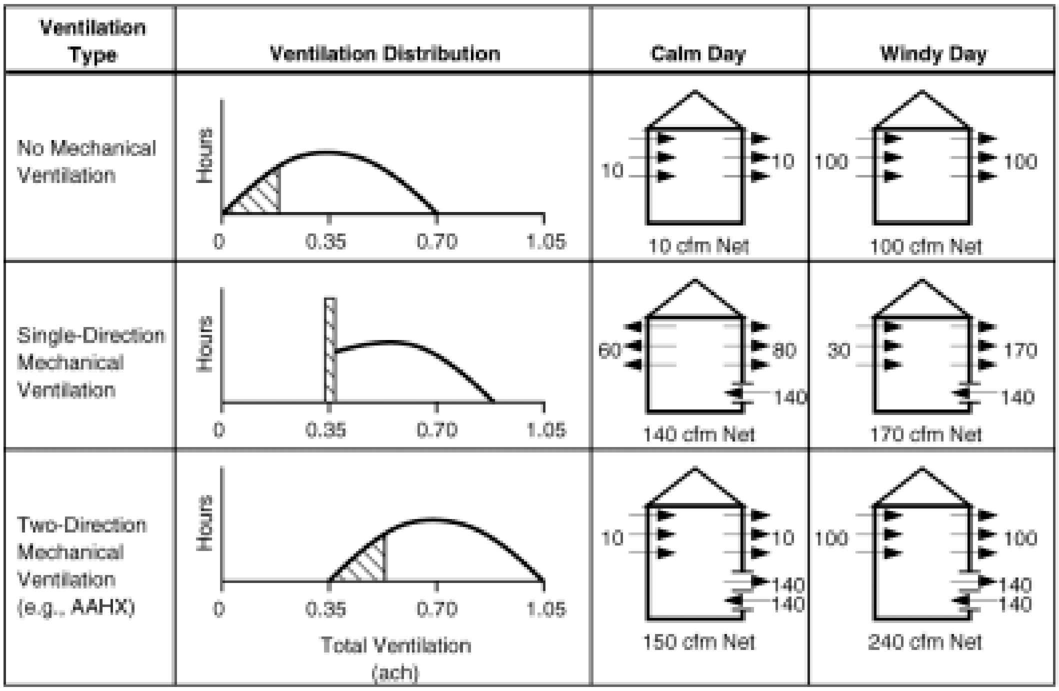


Figure 1. Comparison of Ventilation Types

mechanical ventilation such that there is little overventilation. In addition to the declining economic benefit, it is possible to build a house tight enough that single-direction ventilation would pressurize the house excessively (more than 10 to 20 Pa) in order to force air out through the cracks. With the combination of decreased savings and excessive house pressure, two-direction ventilation is recommended for use in homes with an average natural infiltration rate of less than 0.1 ach. This is quite tight and would probably only include supertight homes (perhaps the tightest 1% of homes being built). Most modern construction would be in the range where single-direction ventilation would be feasible. The effects of changing house tightness will be discussed later.

In addition to the issue of pressure magnitude, it must be decided whether a positive or negative pressure should be maintained. A single-direction flow from inside to outside (such as exhaust fans) would negatively pressurize the house, resulting in problems with gas appliance stack flow, increased radon infiltration, and possibly even uncomfortable drafts. Thus, in homes with gas appliances or possible radon problems, an outward-directed ventilation method probably should not be used. A positive house pressure could in some cases aggravate a problem with condensation or frosting inside of walls as humid indoor air leaks through the cold building shell. This problem is not caused by pressurization, however, since air leaks through the building shell simply through natural infiltration. The lower humidity resulting from the added ventilation will help reduce frosting, whereas increased flow will probably tend to increase frosting. The net effect is not intuitively clear, but this issue should be resolved before positive pressurization of the house is either abandoned or implemented.

Return Duct Ventilation

The ventilation method considered in this section brings additional fresh air into the return duct by increasing the make-up air duct size (and thus airflow) and/or setting a minimum fan on-time. Fan power is not considered to change for various fresh air flow rates; thus, the only cost of increasing the fresh air flow is due to the additional thermal load incurred. Fan energy use does increase with increased fan on-time. It may turn out that because of higher space pressure from increased fresh air flow, the furnace fan itself cannot draw in enough fresh air. Also, a large open duct to the outdoors might be too susceptible to wind or temperature effects and actually behave more like another opening in the house shell than like the constant flow source desired. A blower may be required in the make-up air duct to provide consistent airflows of the desired magnitude.

A matrix of annual simulations was made with minimum fan on-times of 10, 15, 20, 30, and 60 min/h and with fresh air flow rates of 84, 134, 140, 268, and 300 cfm (39.65, 63.25, 66.1, 126.5, and 141.6 L/s, respectively). Figure 2 shows the simulation results in percent of hours below the ASHRAE-recommended level of 0.35 ach as a function of ventilation cost (cost above the no-ventilation reference case). Thus, the better performing systems are in the lower left of the graph. Each curve in the more horizontal family represents a single fresh air flow rate over a range of minimum hourly fan on-times. The curves in the more vertical family represent varying fresh air flow for a single minimum hourly fan on-time.

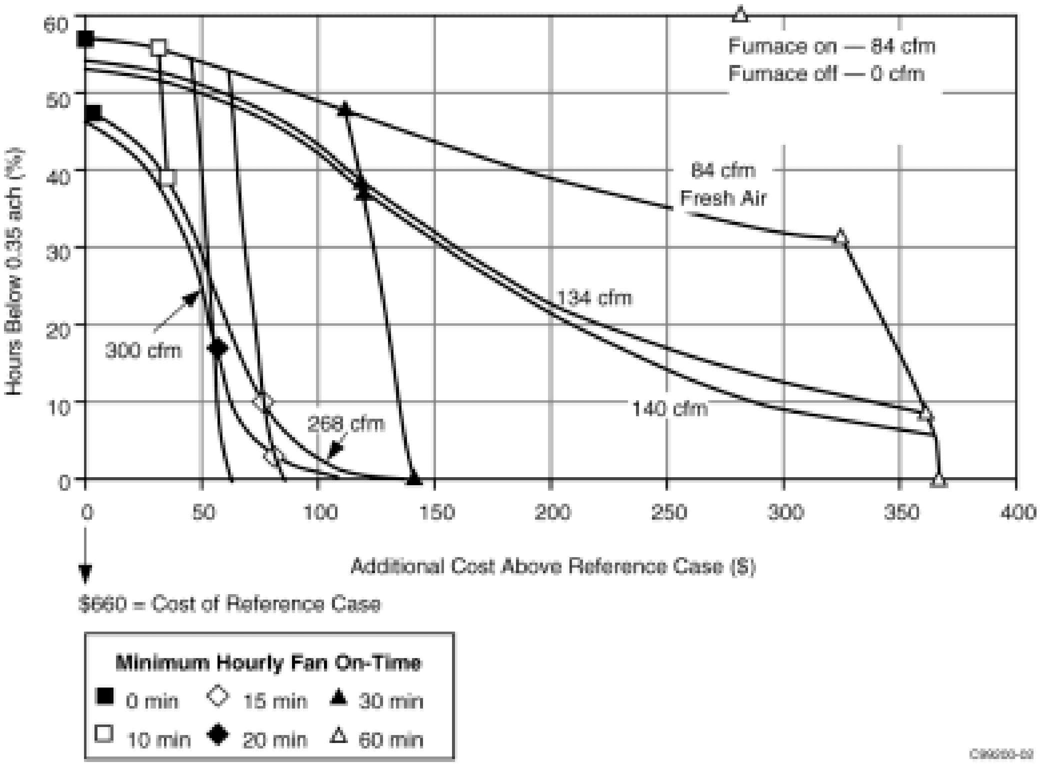


Figure 2. Cost of Control Strategies for Return Duct Ventilation Systems

The data show that the primary factor in the cost of the various strategies is the fan on-time. The strategy with continuous fan operation and 84 cfm (39.65 L/s) of fresh air (the amount drawn into the make-up duct of the reference case) costs $325 per year more than the reference case. Of this, $280 can be attributed to the additional fan operation and only $40 to the increased thermal load of bringing in outdoor air. This division is based on the location of the top point on the graph, which represents a strategy employing continuous fan operation but with only as much fresh air as the reference case. For $40, the number of hours with less than 0.35 ach is reduced from 60% to 30%. Increasing the fresh air intake to 140 cfm (66.1 L/s) to guarantee no hours below 0.35 ach results in a further cost increase of only $30. The $280 cost of running the fan continuously probably cannot be justified on the basis of ventilation alone, but if the fan is run continuously for some other reason, such as air cleaning, the additional $70 per year cost provides vastly improved ventilation by bringing in the additional outdoor air.

If the fan does not need to be run continuously, a lower hourly minimum fan on-time and a higher fresh air flow rate can be used to more economically guarantee 0.35 ach. Using a minimum fan on-time of 30 min/h and a fresh air flow of 268 cfm (126.5 L/s) results in a yearly cost only $140 higher than the reference case and still provides 0.35 ach minimum throughout the year. Other combinations to provide 0.35 ach are possible, so the optimal solution should be determined if this strategy is to be used. Reducing the fan on-time and increasing the fresh air flow beyond that shown in the graph may or may not continue to reduce the total cost of the 0.35-ach ventilation. Although that is the trend indicated, eventually the fan will need to be on sufficiently more than the minimum so that the energy penalty from the resulting excess fresh air (at times of extreme outdoor temperature) will outweigh the savings from the reduced fan operation at moderate outdoor temperatures. Another reason to avoid excessive fresh air flow rates is that the duct to the outside would have to be quite large. For instance, the system modeled would need a fresh air duct half the size of the trunk of the return duct to provide 400 cfm (188.8 L/s) of fresh air (one-third of the total return flow). Even 268 cfm (126.5 L/s) would require an unusually large duct to the outdoors (about one-fourth the size of the trunk of the return duct). These figures may even be optimistic, since they do not take into account the fact that the house will be pressurized by the fresh air flow, resulting in a higher proportion of the total flow coming back from the space than would be expected based on the duct area ratios. Since performance improves with increasing airflow rates up to 400 cfm (188.8 L/s), the best way to implement this ventilation method is to first select the fresh air flow rate to be as large as practical (almost certainly not more than 300 cfm (141.6 L/s)) and then, based on the house volume, determine the minimum fan on-time. This will decrease the required fan on-time and thereby minimize the cost, since fan power is the dominant cost factor for the range of reasonable fresh air flows.

Rather than selecting an airflow and fan on-time that assure zero hours with less than 0.35 ach, it is probably more cost-effective to ventilate at a slightly lower level and allow it to fall below 0.3 ach for a few hours. The level of mechanical ventilation can be reduced sufficiently to provide significant cost savings without resulting in too many hours with total ventilation below 0.35 ach because there is usually some significant natural ventilation. Using the 268-cfm (126.5 L/s) curve as an example, reducing the fan on-time from 30 to 20 min/h minimum results in a savings of $65 (or nearly 50% of the total cost of ventilation) with less than 0.35 ach for 10% of the hours. A disadvantage of this option is that it is more difficult to apply since the number of hours with less than 0.35 ach for a given mechanical ventilation shortage depends on the tightness of the house. A perfectly tight house would always be below 0.35 ach, whereas a very leaky house might very rarely be. Also, there is no guarantee that the ventilation system will always maintain the ASHRAE-recommended minimum ventilation rate.

Fresh Air Fan Ventilation

As mentioned earlier, rather than drawing in fresh air with the furnace blower itself, it may be necessary (and perhaps more economical) to force the fresh air in with a separate fan in the make-up air duct. This way, the furnace fan would run no more than required and the fresh air fan would run the 20 or 30 min needed for adequate ventilation. This would save energy, since only the 200 or 300 cfm (94.4 or 141.6 L/s) needed for ventilation would be going through the ventilation fan, instead of the 1,200 cfm (566.4 L/s) the furnace fan must move to draw in 200 or 300 cfm (94.4 or 141.6 L/s) of fresh air. A 250-cfm (118.0 L/s) 150-W blower could provide the required fresh air by operating 30 min/h for $38 per year. For this amount of money, the furnace blower could only be on an additional 6 min/h on average, which is not enough to achieve 30 min/h minimum. Furnace fan operation of 30 min/h minimum adds about $100 per year in fan power costs over the reference case (fan on only when needed).

One possible problem with this ventilation method is the distribution of fresh air through the duct system with a flow of only 140 cfm (66.1 L/s) or perhaps 280 cfm (132.2 L/s) (at 30 min/h or 60 min/hr operation, respectively). In winter, the cold air being brought in would tend to trickle out of the lowest supply vents in the house rather than being distributed to all zones. If this is determined to be unacceptable, the furnace fan would again have to be run whenever the ventilation fan is on, which would eliminate any possibility of an economic advantage with the fresh air blower. However, as stated above, running a ventilation fan with the furnace fan would only cost an additional $38 annually. It would be desirable to avoid this cost, if possible, but it would not be prohibitive if a fan was deemed necessary. Additional simulation and analysis are required to further explore this concept.

Exhaust Fan Ventilation

Under the exhaust fan ventilation method, either the bathroom fan, the range hood, or both are operated intermittently or continuously to provide the desired level of ventilation. The bathroom fan in the simulated house provides 50 cfm (23.6 L/s) of ventilation and uses 33 W; the range hood provides 100 cfm (47.2 L/s) and uses 67 W. If both fans are run continuously, the 150 cfm (70.8 L/s) provided would be sufficient to guarantee the ASHRAE-recommended 0.35 ach (actually, only 139 cfm (65.61 L/s) is required). One drawback of this ventilation method is that it negatively pressurizes the house. The magnitude of the pressurization and the resulting effect on furnace stack flow and radon are not predicted in the model; thus, no specific conclusions are drawn about the significance of the negative pressurization.

Figure 3 shows the number of hours with less than 0.35 ach for this ventilation method compared to the results presented earlier for the system with fresh air drawn into the return duct. Two curves are displayed, one for continuous operation over a varying number of hours per day and the other for operating a varying number of minutes out of each hour. The points plotted on the minutes-per-hour curve are for 30, 40, and 60 min. For the hours-per-day line, the points plotted are for 3, 6, 11, 12, and 24 hr per day. Strategies with just a few hours of daily operation are of interest because many timed exhaust fan ventilation systems installed in the northwestern United States are currently set to as little as one hour per day. Clearly, if continuous operation is needed to provide the ASHRAE minimum, a few hours per day of exhaust fan operation will not provide adequate ventilation.

The simulation results show exhaust fan ventilation to be less cost-effective than the return duct ventilation options. Although the exhaust fan ventilation method requires less total electric energy for the fans (furnace and exhaust) than does the other method, it apparently tends to overventilate more at extreme outdoor temperatures when it is obviously costly to overventilate. Apart from any ventilation strategy, the house is generally positively pressurized, and the exhaust fans bring it back to (and past) neutral pressure and thus do not reduce the natural infiltration as much as a positive pressure ventilation system would. This factor is specific to the particular make-up and stack flow rates used and should not be construed as promoting positive pressure over negative pressure.

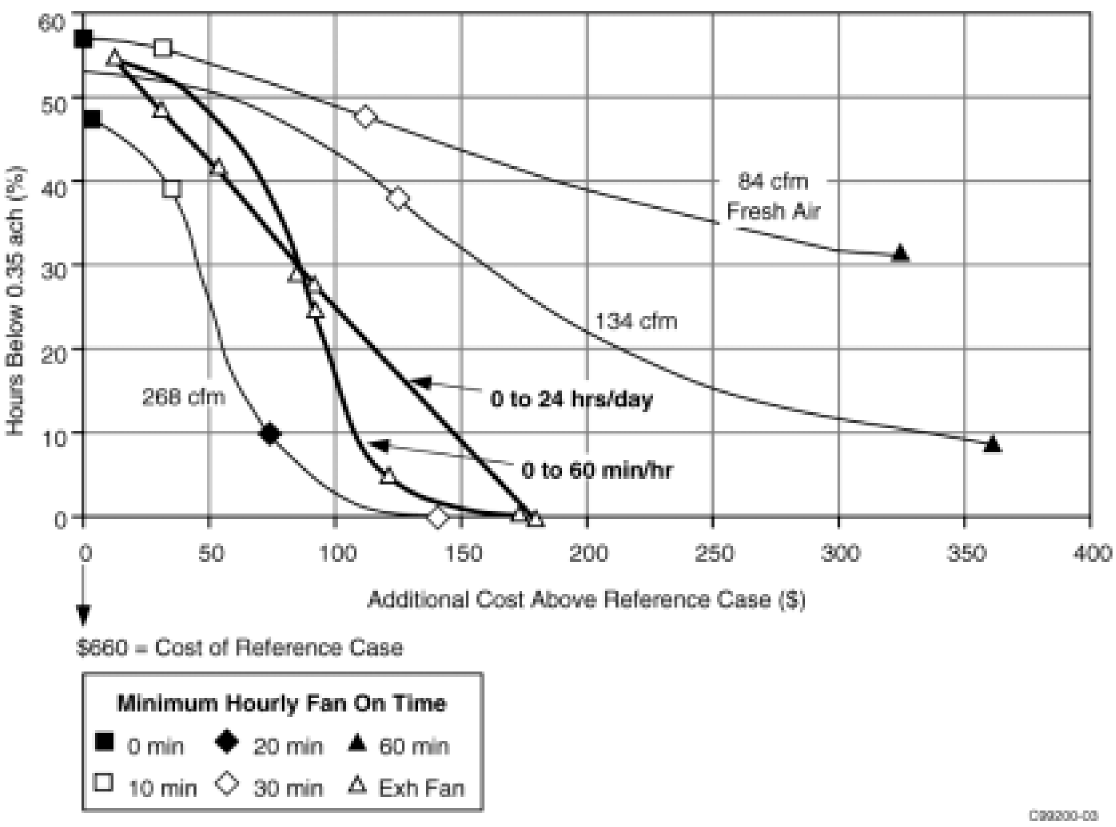


Figure 3. Comparison of Exhaust Fan Ventilation and Return Duct Ventilation

The linear relationship for the hours-per-day plot is due to the fact that the number of hours with less than 0.35 ach and the cost of ventilation are both roughly proportional to the number of hours the fans are. The shape of the minutes-per-hour curve is due to the bell-shaped distribution of the natural infiltration. The total amount of ventilation for the minutes-per-hour curve is actually no better than for the hours-per-day plot, but it is spread more evenly over all hours of the day and consequently provides more hours with greater than 0.35 ach when total ventilation is insufficient to provide more than 0.35 ach for all hours.

Heat Recovery Ventilation

Using a heat recovery ventilator significantly reduces the annual cost of two-direction ventilation, but compared to the single-direction ventilation methods, is not sufficient to offset the high initial cost. Figure 4 shows that for zero hours with less than 0.35 ach, the savings are $75 per year for the HRV over the return duct ventilation system. Savings over continuous exhaust fan ventilation are $100 per year. For an approximate installed cost of $1,200 for an HRV, the payback period would be more than 10 years.

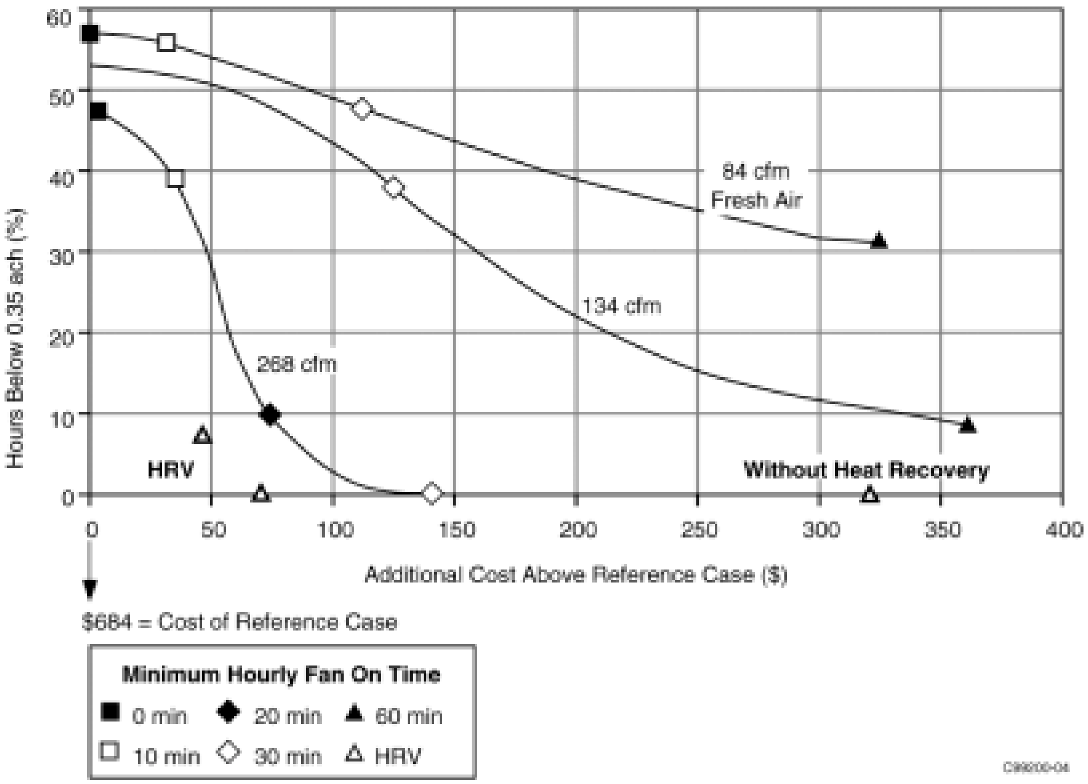


Figure 4. Comparison of Heat Recovery Ventilator and Return Duct Ventilation

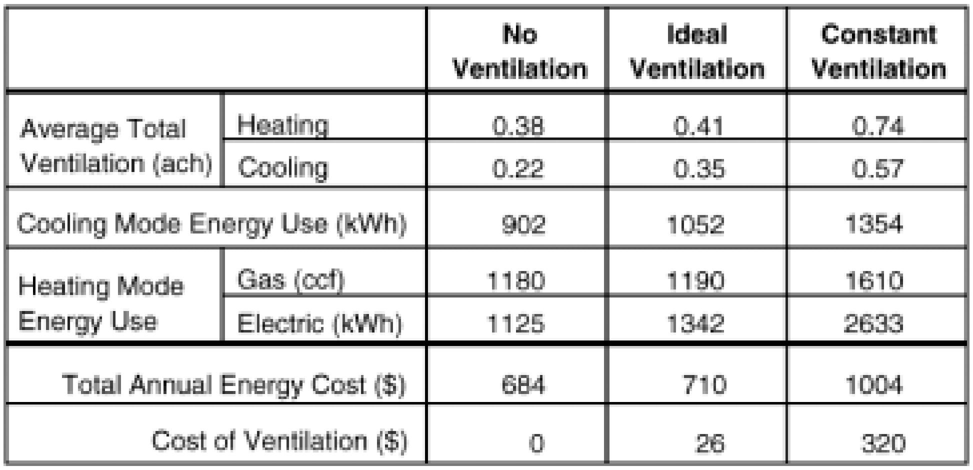
In tight-house applications where there are not enough cracks through which a single-direction fan could force air, two-direction ventilation may be necessary. In this case, the savings resulting from using an HRV over the two-direction non-heat-recovery ventilation case would be $250 per year, providing a 5-year payback. In some cases, a distributed exhaust system similar to that used with an HRV may be desirable for non-economic reasons (e.g., to draw exhaust air from areas that typically have high pollutant levels, such as along ceilings, in bathrooms, etc.). In these cases, where the installation cost associated with a single-direction distributed exhaust system is incurred anyway, it may be worth the additional cost to include an HRV.

The simulation results thus far are based on weather data for Minneapolis and relatively low energy costs ($0.50 per therm for gas and $0.06 per kWh for electricity). The HRV would probably be less attractive for other climates, since most would be less severe than Minneapolis, and hence there would be less benefit from heat recovery. Higher gas rates should make the HRV more attractive, whereas higher electric rates may make it less attractive, since it saves heating cost at the expense of fan cost. For costs of $0.75 per therm and $0.12 per kWh, the payback period would be 9 years or more for the same house and climate.

Estimation of Natural Infiltration

The discussion thus far has covered ventilation methods that provide continuous ventilation without any consideration of the natural ventilation already present. If the amount of natural ventilation is known, so excess mechanical ventilation can be eliminated, the cost of maintaining a minimum of 0.35 ach can be reduced dramatically. Table 1 shows that by accurately predicting natural ventilation and only adding mechanical ventilation up to 0.35 ach (designated as "ideal ventilation"), almost the entire cost of mechanical ventilation can be saved. This amounts to savings of about $150 per year over constant single-direction ventilation and $300 per year for two-direction ventilation. The key to achieving these savings is to find a simple way to estimate the natural ventilation reasonably accurately. It is most beneficial to have an accurate estimate at extreme outdoor temperature conditions when the cost of overventilation is greatest.

Table 1. Energy and Cost for Providing Minimum Ventilation



		No Ventilation	Ideal Ventilation	Constant Ventilation
Average Total Ventilation (ach)	Heating	0.38	0.41	0.74
	Cooling	0.22	0.35	0.57
Cooling Mode Energy Use (kWh)		902	1052	1354
Heating Mode Energy Use	Gas (ccf)	1180	1190	1610
	Electric (kWh)	1125	1342	2633
Total Annual Energy Cost ($)		684	710	1004
Cost of Ventilation ($)		0	26	320

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Attempts were made to identify parameters, such as the temperature error signal in a thermostat or the outside air temperature, from which natural infiltration could be estimated, but no such correlations could be found. One problem confronting all infiltration estimation techniques is the initial determination of house tightness. No matter how good the correlation between natural infiltration and whatever parameter is used, the estimation of infiltration is only as good as the starting reference used (e.g., a data point or a quantitative estimate of the tightness of the house). From that point, the change in infiltration can be determined from whatever correlation is being used. Unless a blower-door test (in which a known pressure is applied to the house and the leakage area is determined from the resulting flow) can be done as part of the ventilation system installation, the only way to determine house tightness is to estimate it based on the building practices used. Thus, the one advantage of the strategies described earlier, which provide the entire 0.35 ach mechanically, is that an installer need only know the volume of a particular house to select the proper fresh air flow rate.

Effect of Changing House Tightness

Since the costs presented thus far are all based on a single house tightness, this section describes the effect on the results and conclusions if a less tight house is used. Figure 5 shows the effects of changing house tightness on the cost of operation for each of the major types of ventilation being considered: constant two-direction, constant single-direction, constant with heat recovery and ideal ventilation. The data points shown represent simulation results for the single house modeled, and the curves are predictions of how those results would change as the house tightness changes. These curves should be reasonably accurate because numerous intuitive factors define many of their parts.

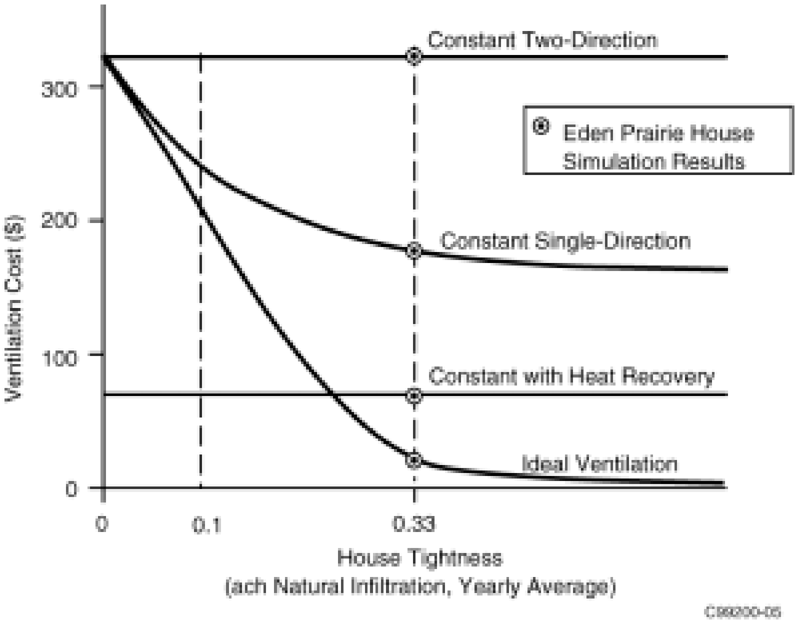


Figure 5. Predicted Effect of House Tightness on Costs of Ventilation Methods

The lines labeled "two-direction" and "heat recovery" are perfectly horizontal because, as discussed earlier (see Single- vs. Two-Direction Ventilation), the two-direction method provides the same net increase in ventilation and thus incurs the same additional cost, regardless of the infiltration level. The "single-direction" and "ideal" curves have the same cost as the "two-direction" line at an average infiltration of zero because, without infiltration, all three ventilation methods would provide exactly the same total ventilation of 0.35 ach. As the average infiltration rate increases from zero, the "single-direction" and "ideal" curves are coincident because, until infiltration is sufficiently high that at times the flows leaking in are not completely reversed by the single-direction ventilation, the total ventilation will remain exactly 0.35 ach. The cost of ideal ventilation approaches zero as average infiltration increases because ideal ventilation eventually will be no ventilation. Single-direction ventilation approaches roughly half the cost of two-direction ventilation because, as discussed earlier, when infiltration is high, the net ventilation increase of a single-direction method is half the magnitude of the single-direction flow. Additional simulations are necessary to determine the exact shape of the two curves, including the value of their mutual slope at zero average infiltration.

Figure 5 shows that for tight homes where two-direction ventilation is required to avoid excessive house pressure, the cost savings of an HRV over any other option are sufficient to make it attractive from an economic standpoint as well. For a perfectly tight house, an HRV would save approximately $250 over any non-heat-recovery ventilation method, resulting in a payback period of less than 5 years. At a yearly average infiltration rate of 0.1 ach, which was suggested in earlier discussions as the cutoff between single-direction and two-direction ventilation, the payback of an HRV over single-direction or ideal ventilation would be about 7 to 10 years. The exact value cannot be determined because the actual slope of the single-direction and ideal ventilation curves is not known. Due to the relatively long payback, if pressure considerations would allow use of single-direction ventilation in homes tighter than 0.1 ach, this cutoff might be reduced further.

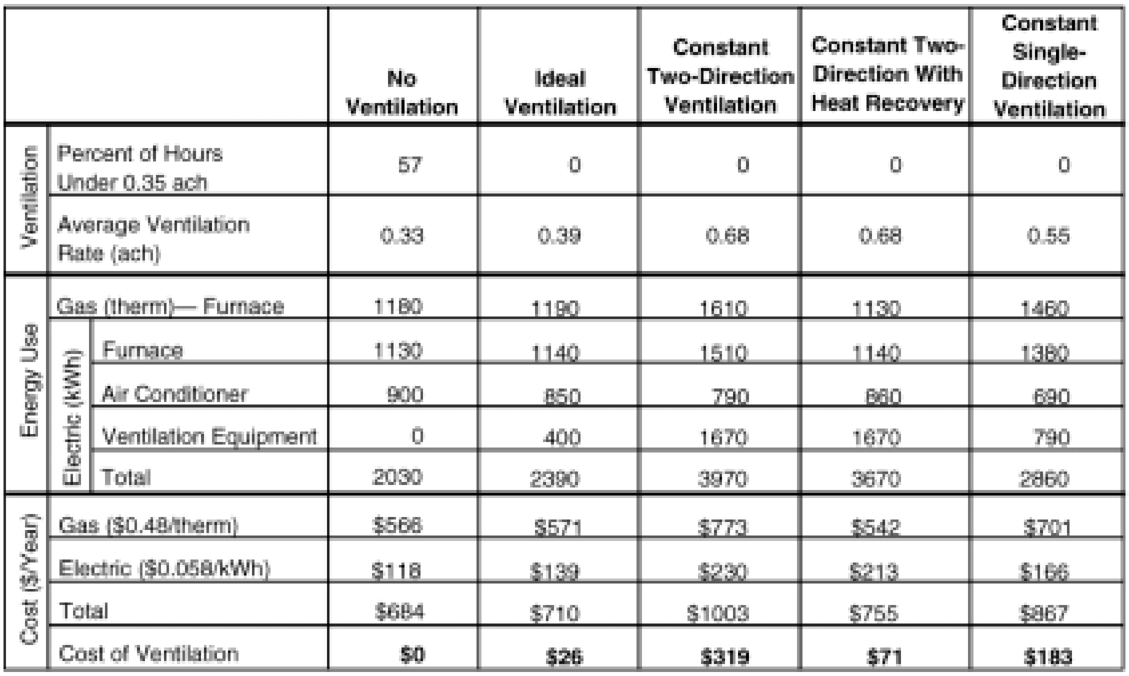
Summary and Conclusions

Growing concerns over indoor air quality have resulted in a need to compare residential ventilation methods and define applicable ventilation control strategies. The objective of this study was to use existing dynamic simulation models and the GEMS analysis tool to investigate residential ventilation control strategies that would provide air quality benefit with minimum energy penalty while maintaining comfort. The tasks involved evaluating various ventilation methods and control strategies to determine the cost of maintaining the ASHRAE-recommended 0.35-ach minimum ventilation level. Simulations for both the heating and cooling seasons were conducted using a heat recovery ventilator and several simple ventilation methods.

Table 2 shows the results of five annual runs that provide an overview of the simulation analysis. Ventilation performance, energy use, and annual energy cost are presented. The first column is the base or "no ventilation" case. Next is the case where the natural infiltration is known exactly and mechanical ventilation (two-direction without heat recovery) is added, as necessary, to achieve the desired level. The third column is for a constant 0.35-ach two-direction mechanical ventilation without heat recovery, and the fourth column is for the same conditions but with heat recovery. The last column is for a constant 0.35-ach single-direction mechanical ventilation. Note that all the ventilation methods presented here meet the goal of providing at least 0.35 ach of total ventilation. These five runs capture most of the important conclusions regarding heat recovery, single- versus two-direction ventilation, and the importance of knowing the natural infiltration level to ventilate efficiently. The results of this study are based on Minneapolis weather data and relatively low energy costs ($0.50 per therm for gas and $0.06 per kWh for electricity).

To ventilate efficiently, it was surmised that an accurate estimate of the natural infiltration would be needed, so that the proper amount of mechanical ventilation could be added to achieve the desired total ventilation level. When a comparison of ideal and "constant" two-direction ventilation (columns two and three) showed a savings of nearly $300 per year, an effort was made to find a parameter, such as the temperature error signal in a thermostat or the outside air temperature, from which natural infiltration could be estimated. Neither of these parameters correlated well with natural infiltration.

Table 2. Energy and Cost Comparisons for Different Ventilation Control Strategies



			No Ventilation	Ideal Ventilation	Constant Two-Direction Ventilation	Constant Two-Direction With Heat Recovery	Constant Single-Direction Ventilation
Ventilation	Percent of Hours Under 0.35 ach		57	0	0	0	0
	Average Ventilation Rate (ach)		0.33	0.39	0.68	0.68	0.55
Energy Use	Gas (therm)— Furnace		1180	1190	1610	1130	1460
	Electric (kWh)	Furnace	1130	1140	1510	1140	1380
		Air Conditioner	900	850	790	860	690
		Ventilation Equipment	0	400	1670	1670	790
		Total	2030	2390	3970	3670	2860
Cost ($/Year)	Gas ($0.48/therm)		$566	$571	$773	$542	$701
	Electric ($0.058/kWh)		$118	$139	$230	$213	$166
	Total		$684	$710	$1003	$755	$867
	Cost of Ventilation		**$0**	**$26**	**$319**	**$71**	**$183**

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From the analysis of simple ventilation methods, single-direction ventilation was found to partially compensate for high natural infiltration levels and thus can save about half the cost of ventilating with a two-direction method without heat recovery. The last column of Table 2 represents continuous exhaust fan operation providing 0.35-ach mechanical ventilation. This strategy did not produce the lowest annual cost of the single-direction ventilation methods considered, but it is easy to implement and requires no initial investment (assuming kitchen and bath exhaust fans are installed per code). Other single-direction ventilation methods, such as connecting a fresh air duct to the return plenum, had annual costs as low as $140. Where pressure considerations permit, single-direction ventilation was determined to be a better option than two-direction ventilation without heat recovery.

Using an HRV also significantly reduced the annual cost of two-direction ventilation, but compared to the single-direction ventilation methods, not enough to offset the high initial cost. With savings of approximately $100 per year, as shown in Table 2, and an installed cost of $1,200 for the HRV, the payback period would be about 12 years. In tight house applications where there are insufficient cracks through which a single-direction fan could force air, two-direction ventilation may be necessary. In this case, the savings from an HRV over the two-direction non-heat-recovery ventilation case would be $250 per year, resulting in a 5-year payback. In some instances, a distributed exhaust system like that used with an HRV may be desired for non-economic reasons, such as to draw exhaust air from areas that typically have high pollutant levels (i.e., along ceilings, in bathrooms). In these cases where the installation cost associated with an exhaust system is incurred anyway, it may be worth the additional cost to include the HRV, rather than using single-direction distributed exhaust.

As previously mentioned, the simulation results presented here are based on weather data for Minneapolis. On first consideration, it seems that going to other climates will probably make the HRV less attractive, since most climates would be less severe than Minneapolis and thus lessen the benefits attributable to heat recovery. Gas rates higher than $0.50/therm should make the HRV more attractive, whereas electric rates of more than $0.06/kWh may make the HRV less attractive, since it saves heating cost at the expense of fan cost.

Additional simulations are required to determine the effectiveness of outdoor temperature as an indicator of natural infiltration, since savings would be increased significantly if excess ventilation could be eliminated. Also, further analysis of the effectiveness of single-direction ventilation in tight homes is necessary. Future tasks should include analysis of the use of thermostat setback as a "no ventilation" indicator and ventilation with an economizer (indoor/outdoor enthalpy).

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