ENERGY EFFICIENT RESIDENTIAL VENTILATION CONTROL

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ABSTRACT
A concept is investigated for the energy efficient control of residential mechanical ventilation in response to outdoor air temperature and the corresponding stack-driven infiltration. The control concept takes advantage of the natural air leakage characteristics of a house and the ability of temperature-driven stack infiltration to provide ventilation air to the house. As the outdoor to indoor temperature difference increases and natural infiltration increases, the fan operation is reduced, thereby minimizing over-ventilation. By reducing over-ventilation, the energy use associated with providing ventilation air (fan, heating, and cooling) is reduced when compared to a continuous or duty-cycle ventilation control scheme. Analysis results are presented for a test house in several climate zones to demonstrate reduction in ventilation energy use with the proposed control concept. For an unbalanced system in a moderately tight house, energy use is reduced by 26 to 30% for the climates investigated. For a two-story house, the use of temperature-based control allows a simple unbalanced ventilation system to operate with a total energy use comparable to a balanced system with heat recovery, in the three climates investigated, for all but the tightest houses. The proposed ventilation control method is shown to be an effective method for providing energy efficient residential ventilation control.

KEYWORDS

Mechanical ventilation control, Energy efficient, Temperature, Airtightness, Infiltration

INTRODUCTION

There is a need to provide effective ventilation solutions for houses to help promote good indoor air quality. There has been an increased awareness of this issue as houses are built with increasing airtightness and code jurisdictions develop requirements for ventilation. Effective residential ventilation systems are needed to minimize energy use and other impacts on the house and its occupants.

A number of investigations of residential ventilation have been conducted and many have addressed the energy impacts of ventilation, e.g., Roberson et al. (1998); however, very few investigations have evaluated the effects of mechanical ventilation control. Research sponsored by EPRI, Honeywell Inc. (1993), evaluated residential ventilation control approaches including demand control based on carbon dioxide measurements. There is a lack of published work related to residential ventilation control approaches and their impact on energy use.

A residential mechanical ventilation control approach has been proposed by Holton and Temple (2002), and has the potential to reduce energy use associated with ventilation. The control is based on outdoor air temperature and reduces mechanical ventilation when natural infiltration, due to stack effect, is available to provide ventilation.

The current investigation will focus on an evaluation of the energy savings associated with the proposed temperature-based control concept. The investigation considers the impact of climate, house characteristics, and system type on the energy use associated with ventilation. An issue that has not been addressed as part of this study is that of ventilation effectiveness or distribution of the ventilation air. Using natural infiltration for ventilation has the drawback of uncontrolled points of entry of the air; however, this infiltration will be present regardless of the ventilation control approach. When a forced-air system is present to provide space conditioning, the same temperature difference that creates stack-driven infiltration will also create load for the system causing the central fan to operate and distribute the ventilation air. This investigation will focus on the energy savings associated with the proposed control approach.

ANALYSIS

A simple analysis was developed in order to evaluate the potential energy savings associated with the proposed ventilation control approach. The first part of the analysis is the prediction of the net ventilation airflow due to the superposition of infiltration and mechanical ventilation. The second part of the analysis is the prediction of ventilation energy use associated with fan energy use for mechanical ventilation and required heating and cooling to temper the ventilation air.

The total ventilation airflow rate depends on the natural infiltration due to stack effect and mechanical ventilation. For the present analysis infiltration due to wind is not considered. The natural infiltration rate for the house is calculated at each temperature point in the analysis range using Equation 40 from Chapter 26 of ASHRAE Fundamentals (ASHRAE 2001). The natural infiltration is expressed as

$$Q_i = A_L \left(C_S \left|T_i - T_o\right|\right)^{0.5} \qquad (1)$$

where Q_i is the infiltration airflow rate, A_L is the effective leakage area (ELA) at 4 Pa, $T_i - T_o$ is the indoor to outdoor dry bulb temperature difference, and C_s is the stack coefficient based on the number of stories above grade as indicated in Table 1.

Table 1
Stack Coefficients

Stack Coefficient	English $cfm^2/(in^4\ °F)$	Metric $(L/s)^2/(cm^4\ °C)$
1 story	0.0150	0.000145
2 story	0.0299	0.000290
3 story	0.0449	0.000435

The effective leakage area for the house is typically determined from an air leakage test conducted on the house, such as a blower door test.

The net ventilation rate is determined for each temperature point in the design range for the house based on the interaction of infiltration and mechanical ventilation. One method is to use superposition based on quadrature as suggested by Sherman (1992) and presented in Chapter 26 of ASHRAE Fundamentals (ASHRAE 2001). Mechanical ventilation may be balanced supply and exhaust, Q_{bal}, from a device such as a heat recovery ventilator (HRV), energy recovery ventilator (ERV), or balanced flow fan. Alternatively, mechanical ventilation may be unbalanced, Q_f, when provided by a supply or exhaust fan. The ventilation device flow rate may be equal to or greater than the ventilation requirement, Q_v. The total ventilation, Q_t, as presented in Equation 43 of Chapter 26 of ASHRAE Fundamentals (2001), can be expressed as

$$Q_t = Q_{bal} + \sqrt{Q_f^2 + Q_i^2} \tag{2}$$

The analysis of the net ventilation depends on the system type and the method of fan control. The fan can be controlled by intermittent operation or modulation. This investigation focuses on intermittent operation where the fan is operated a fraction of each hour. Two systems are considered: an unbalanced system with a single fan and a balanced system using an HRV.

For a balanced system, the mechanical ventilation does not interact with the infiltration and the analysis only needs to address the run-time of the ventilation device. A parameter F_v is defined as the run-time fraction for intermittent operation. The net ventilation rate, Q_{net}, can then be expressed as

$$Q_{net} = F_v Q_{bal} + Q_i \tag{3}$$

The run-time fraction F_v is determined by setting Q_{net} equal to Q_v. The parameter F_v cannot be less than zero, so over-ventilation due to infiltration cannot be eliminated. Over-ventilation can be reduced by limiting the operation of the mechanical ventilation as the indoor to outdoor temperature difference increases.

An unbalanced system has a mechanical ventilation device with a capacity Q_f and the total ventilation rate, with the fan operating, can be expressed as

$$Q_t = \sqrt{Q_f^2 + Q_i^2} \tag{4}$$

The parameter F_v is again used as the run-time fraction for intermittent operation and the net ventilation rate, Q_{net}, can then be expressed as

$$Q_{net} = F_v Q_t + (1 - F_v) Q_i \tag{5}$$

The run-time fraction F_v is determined by setting Q_{net} equal to Q_v. As in the previous case, the parameter F_v cannot be less than zero, so over-ventilation due to infiltration cannot be eliminated. In this case there is a significant interaction between infiltration and mechanical ventilation. Mechanical ventilation can be controlled to limit over-ventilation when natural infiltration is available.

The analysis of predicted energy use for ventilation is based on the simplified bin method. Energy use is estimated for fan operation and the sensible heating and cooling required to temper the net ventilation airflow (infiltration and mechanical ventilation).

The fan energy use at each bin is computed based on the run-time fraction, F_v, the bin hours, N, and the fan (unbalanced or balanced) rated input power, P_f, and can be expressed for an individual bin as

$$E_f = NF_v P_f \quad (6)$$

The sensible heating and cooling energy use to temper ventilation air are included in the analysis. Energy use associated with latent loads (dehumidification) is not addressed as part of this study. The sensible heating and cooling energy use for an unbalanced system are computed using the net ventilation airflow rate at each bin, as

$$E_s = N\rho c_p Q_{net}\left(T_o - T_i\right) \quad (7)$$

where ρ is the air density and c_p is the air specific heat.

Sensible heating and cooling energy use to temper ventilation air for a balanced system are computed using the infiltration airflow rate and balanced fan airflow rate as

$$E_s = N\rho c_p\left(Q_i\left(T_o - T_i\right) + F_v Q_{bal}\left(T_{supply} - T_i\right)\right) \quad (8)$$

With sensible heat recovery (HRV) the mechanical ventilation supply temperature, T_{supply}, is computed based on the apparent sensible effectiveness, ε, as

$$T_{supply} = \varepsilon(T_i - T_o) + T_o \quad (9)$$

A test house was defined to illustrate the potential energy savings associated with the proposed ventilation control method. The test house is a two-story home with 2,050 square feet (190 square meters) of conditioned space and four bedrooms. The design ventilation rate for the house is 58 cfm (27.4 L/s). The ELA at 4 Pa was set at 64 in^2 (413 cm^2) to represent a moderately tight house with an airtightness level of 4 air changes per hour at 50 Pa. The base case test house is considered to have unbalanced mechanical ventilation with a supply fan. The energy performance for an exhaust system would be equivalent. A representative ventilation fan was selected with a capacity of 90 cfm (42.5 L/s) at 0.2 in wc (50 Pa) and 16 watts input power. The base system is considered to operate on a duty-cycle so that the energy use is not impacted by the excess fan capacity (90 cfm versus 58 cfm). For duty-cycle control, the supply fan has a run-time fraction of 0.64 (58 divided by 90). A balanced system is also investigated that uses an HRV with a capacity of 78 cfm (36.8 L/s) at 0.2 in wc (50 Pa) and 92 watts input power, and an apparent sensible effectiveness of 0.89. For duty cycle control, the HRV will have a run-time fraction of 0.74 (58 divided by 78).

The analysis approach is used to investigate the impact on energy use of duty-cycle and temperature-based mechanical ventilation control approaches. The investigation considers the impact of climate using three cities: Minneapolis (cold), Washington, D.C. (mixed-humid), and Phoenix (hot-dry). The investigation also considers house characteristics (stories and leakage) and ventilation system (unbalanced or balanced).

RESULTS

The energy use associated with ventilation for the base case test house (moderately tight) was investigated for the base case of the unbalanced system. The energy use for fan operation and heating and cooling of the net ventilation air (infiltration and mechanical ventilation) were computed for the three analysis cities. The results are summarized in Figure 1 and Table 2 for duty-cycle operation and the proposed control based on outdoor air temperature. Annual energy use is presented in units of million Btu (MMBtu). The control method reduces the total ventilation energy use by 26 to 30% compared to duty-cycle operation. Fan energy use is reduced by 49% in Phoenix to 66% in Minneapolis. The largest energy reduction is a savings of 6.30 MMBtu (1845 kWh) per year for heating in Minneapolis. These results illustrate the potential benefit of minimizing over-ventilation using the proposed control method.

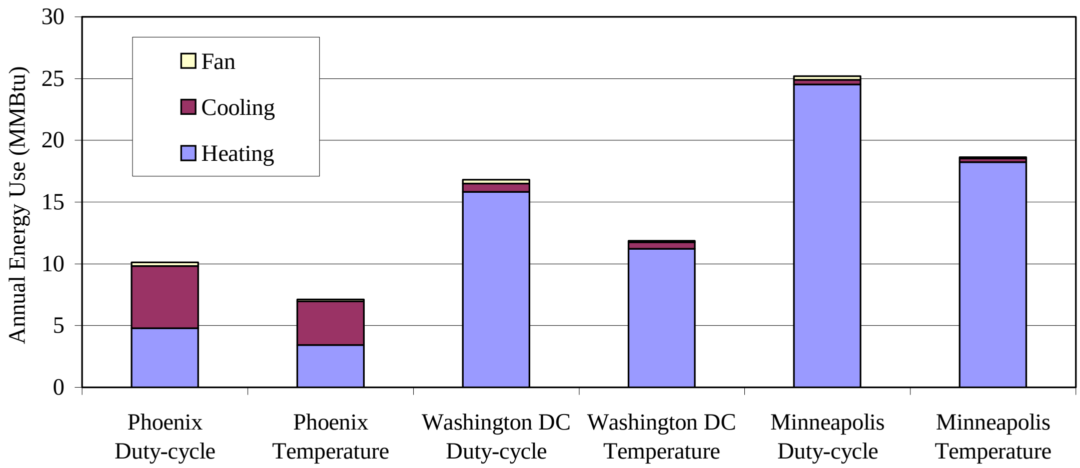


Figure 1. Impact of Climate on Energy Use, Unbalanced System

(Two-story, Moderately Tight House: ELA 64 in^2)

The impact of house height or number of stories on ventilation energy use was investigated for the test house in Minneapolis. The results are summarized in Figure 2. With the duty-cycle control, the annual fan energy use remains the same at 0.31 Btu (90.3 kWh) regardless of the house height. With the temperature-based control, the fan energy use increases with reduction in house height to account for the reduced infiltration. The annual fan energy use is 0.08 Btu (24.4 kWh) for the three-story house compared to 0.16 Btu (45.8 kWh) for the one-story house. In contrast, the heating and cooling energy use decreases with reduction in house height due to the reduced infiltration and associated over-ventilation, resulting in a net energy savings. The results indicate that there is a potential energy savings associated with the control method regardless of house height, at least in a cold climate.

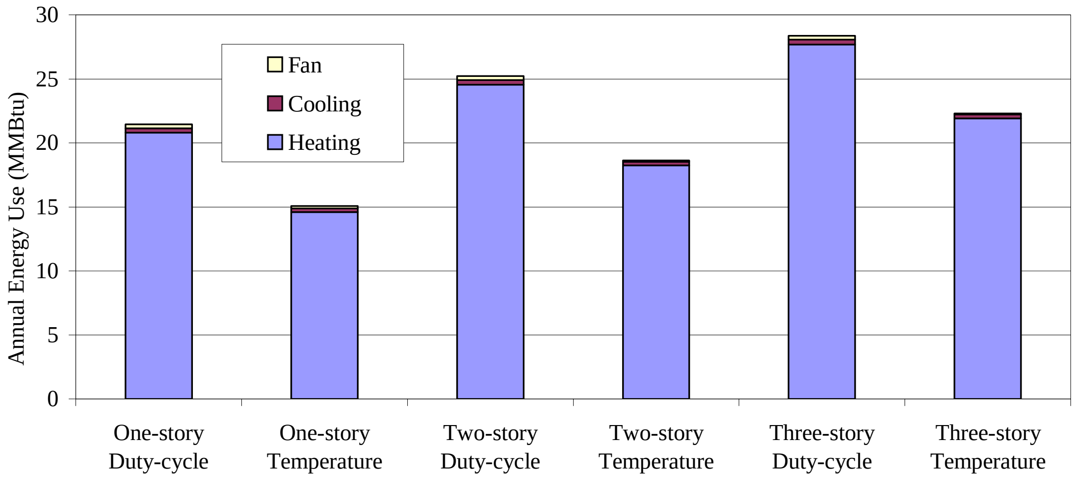


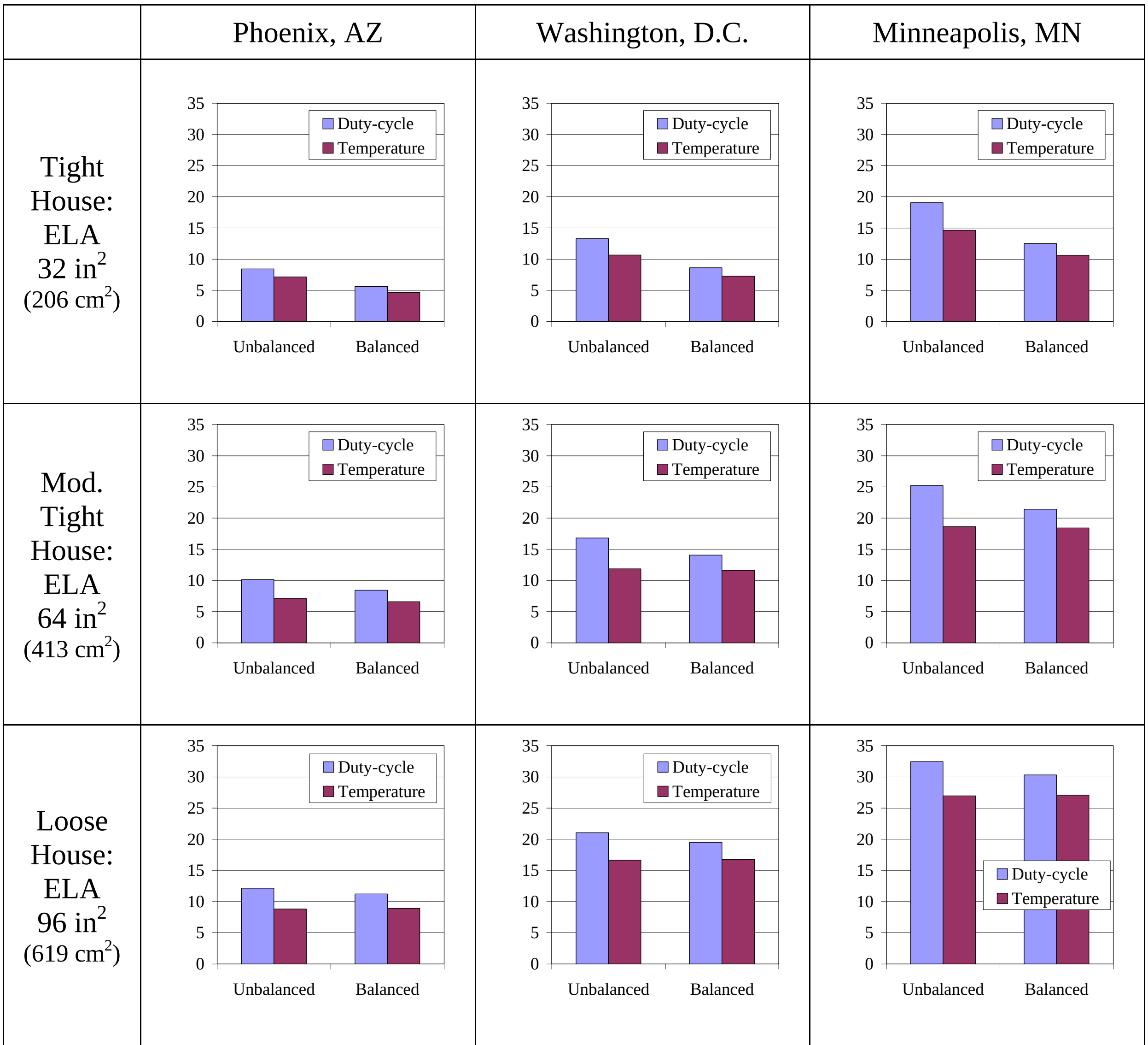
Figure 2. Impact of House Height on Energy Use, Unbalanced System, Minneapolis

(Moderately Tight House: ELA 64 in^2)

Table 2.
Annual Energy Use (Two-story House, ELA 64 in^2)

Annual Energy Use (MMBtu)		**Washington, D.C.**		**Minneapolis, MN**		**Phoenix, AZ**	
		Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced
Duty Cycle	Heating	15.83	11.65	24.54	19.19	4.81	3.12
	Cooling	0.68	0.37	0.37	0.19	5.02	3.26
	Fan	0.31	2.04	0.31	2.04	0.31	2.04
	Total	16.82	14.06	25.22	21.42	10.13	8.42
Temperature	Heating	11.21	10.64	18.24	17.70	3.42	2.82
	Cooling	0.54	0.33	0.30	0.17	3.56	2.95
	Fan	0.12	0.66	0.10	0.55	0.16	0.80
	Total	11.87	11.63	18.64	18.42	7.13	6.57
Savings	Heating	4.62	1.01	6.30	1.49	1.39	0.30
	Cooling	0.14	0.04	0.07	0.02	1.46	0.31
	Fan	0.19	1.38	0.20	1.49	0.15	1.24
	Total	4.95	2.43	6.57	3.00	3.00	1.85

The impact of the combined effects of effective leakage area (ELA) and ventilation system type on ventilation energy use was investigated for the three climates. The results are summarized in Figure 3 and the data for ELA of 64 in^2 (413 cm^2) are presented in Table 2. For the two-story test house with temperature control, an unbalanced system is as energy efficient as a balanced system with heat recovery for a relatively loose house (ELA 96 in^2) in all three climates, e.g., 27.0 Btu (7900 kWh) versus 27.1 Btu (7930 kWh) for Minneapolis. This is also true for the moderately tight house (ELA 64 in^2) in Minneapolis and Washington, D.C. In Phoenix, there is some benefit in using a balanced system with heat recovery at this leakage level. For a tight house (ELA 32 in^2), there is a significant benefit in the use of a balanced system with heat recovery rather than an unbalanced system, in all three climates, with or without the control method. It should be noted that the apparent sensible effectiveness of the HRV for this analysis was 0.89 as indicated in the previous section. These results further illustrate the potential energy savings associated with the proposed temperature-based ventilation control approach.



Note: All values are total annual energy use in units of MMBtu (1 MMBtu = 293 kWh)

Figure 3. Impact of Effective Leakage Area and System Type on Total Energy Use

(Two-story House)

CONCLUSIONS

A temperature-based control method for reducing the energy use associated with residential ventilation has been presented. The method of controlling mechanical ventilation based on outdoor air temperature has been demonstrated to reduce the ventilation energy use for a moderately tight test house with an unbalanced system by 26 to 30% for the climates investigated. In Minneapolis, the control is effective at reducing the ventilation energy use for an unbalanced system in a moderately tight house, regardless of the house height. For a two-story house, the use of temperature-based control allows a simple unbalanced (supply or exhaust) ventilation system to operate with a total energy use comparable to a balanced system with heat recovery (HRV) in the three climates investigated, for all but the tightest houses. The proposed ventilation control method has been shown to be an effective method for providing energy efficient residential ventilation control.

Several aspects of the temperature-based control approach have not been investigated. These include the energy use associated with latent load (dehumidification) from ventilation air, application of the control approach in a hot-humid climate, application of the control approach with higher ventilation rates, and application of the control approach with fan modulation rather than intermittent control. These are all potential topics for future research.

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