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Energy and air quality implications of passive stack ventilation in residential buildings

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ABSTRACT

Ventilation requires energy to transport and condition the incoming air. The energy consumption for ventilation in residential buildings depends on the ventilation rate required to maintain an acceptable indoor air quality. Historically, U.S. residential buildings relied on natural infiltration to provide sufficient ventilation, but as homes get tighter, designed ventilation systems are more frequently required – particularly for new energy efficient homes and retrofitted homes. ASHRAE Standard 62.2 is used to specify the minimum ventilation rate required in residential buildings and compliance is normally achieved with fully mechanical whole-house systems; however, alternative methods may be used to provide the required ventilation when their air quality equivalency has been proven. One appealing method is the use of passive stack ventilation systems. They have been used for centuries to ventilate buildings and are often used in ventilation regulations in other countries. Passive stacks are appealing because they require no fans or electrical supply (which could lead to lower cost) and do not require maintenance (thus being more robust and reliable). The downside to passive stacks is that there is little control of ventilation air flow rates because they rely on stack and wind effects that depend on local time-varying weather. In this study we looked at how passive stacks might be used in different California climates and investigated control methods that can be used to optimize indoor air quality and energy use. The results showed that passive stacks can be used to provide acceptable indoor air quality per ASHRAE 62.2 with the potential to save energy provided that they are sized appropriately and flow controllers are used to limit over-ventilation.

Introduction

In residences indoor air quality is controlled by ventilation that requires energy to transport and condition the incoming air. Standards such as ASHRAE Standard 62.2 (ASHRAE 2007) specify the minimum ventilation rate required in residential buildings. The standard is being used increasingly in the U.S. by various states including: Maine, Vermont, Minnesota, Washington and California. Compliance is normally achieved with fully mechanical whole-house systems; however, alternative methods may be used to provide the required ventilation when their air quality equivalency has been proven. From the perspective of current standards for residential ventilation, such as ASHRAE 62.2, air quality equivalency is the long-term exposure of occupants – typically one-year-long time scale. The energy associated with ventilation has been studied for many years, with most estimates being about one third of the total space conditioning energy consumption of a home (Orme 1998). Recent detailed studies by Sherman and Walker (2008) and Walker and Sherman (2008) found that providing ASHRAE 62.2 compliant ventilation increased space conditioning energy use by about 10% compared to a home that did not meet the minimum ventilation requirements of ASHRAE 62.2. The additional energy use is dominated by space conditioning rather than mechanical fan power – at least for

simple exhaust systems. For more complex Heat Recovery Ventilation (HRV) systems (that are required for energy efficient tight new homes or retrofitted existing homes) the additional energy use was only 5% due to recovery of heating energy. For retrofitted homes, the cost of the mechanical ventilation fan and installation of the electricity supply represent a significant barrier to having a good ventilation system and therefore also to having good indoor air quality, thus making the use of passive systems desirable.

One appealing method to provide ventilation in a home is the use of passive stack ventilation systems. For a passive stack ventilation system the energy used to transport the air is provided by buoyancy and wind effects. The stack essentially works as an exhaust by extracting air from the house and increasing in-flows elsewhere in the building envelope. These systems have been used in European houses for many years. The installation of a stack requires less effort than a mechanical system because no electrical connections are needed and the system is therefore appealing when retrofitting homes. The system does not consume electricity to operate and there are no mechanical components that require periodic maintenance or replacement. The flow in a stack; however, varies depending on its design, the leakage distribution of the house and the local weather. Because air flows are driven by time-varying buoyancy and wind effects, ventilation rates may vary significantly over time. This means that the passive stack can have insufficient air flows resulting in poor air quality and excessive air flows resulting in excess consumption of energy for heating and cooling. More details of passive stack design and performance issues can be found in Axley (2001).

This study aims to determine the magnitude and severity of these effects in terms of acceptable ventilation system performance. It also looks at ways to limit these extremes of high and low passive stack air flows so as to make the system performance less variable. Energy and air quality performance of a single-story house ventilated by a passive stack with and without a flow controller in four California climates were investigated. The four climates cover a wide range so the results can be applied in other geographical locations. The results are used to suggest simplified sizing and control requirements to optimize the indoor air quality and energy use of passive stacks.

Method

A passive stack's impact on energy consumption and indoor air quality of a single-story house was evaluated by yearly simulations of the heat and mass balances of the home. The air flows, heat transfer, heating and cooling system operation and energy use were simulated using a residential building simulation tool that has been used in previous similar studies (Sherman and Walker 2008, and Walker and Sherman 2008). The simulation tool has been verified by comparison to measured data in homes in previous studies (Walker et al. 2005). The simulation program treats the attic volume and house volume as two separate well-mixed zones, but connected for air flow and heat transport and includes heating and cooling system air flows. The program specifically allows individual localized leaks like passive stacks to be modeled as well as distributed envelope leakage, and mechanical system air flows for ventilation, heating and cooling.

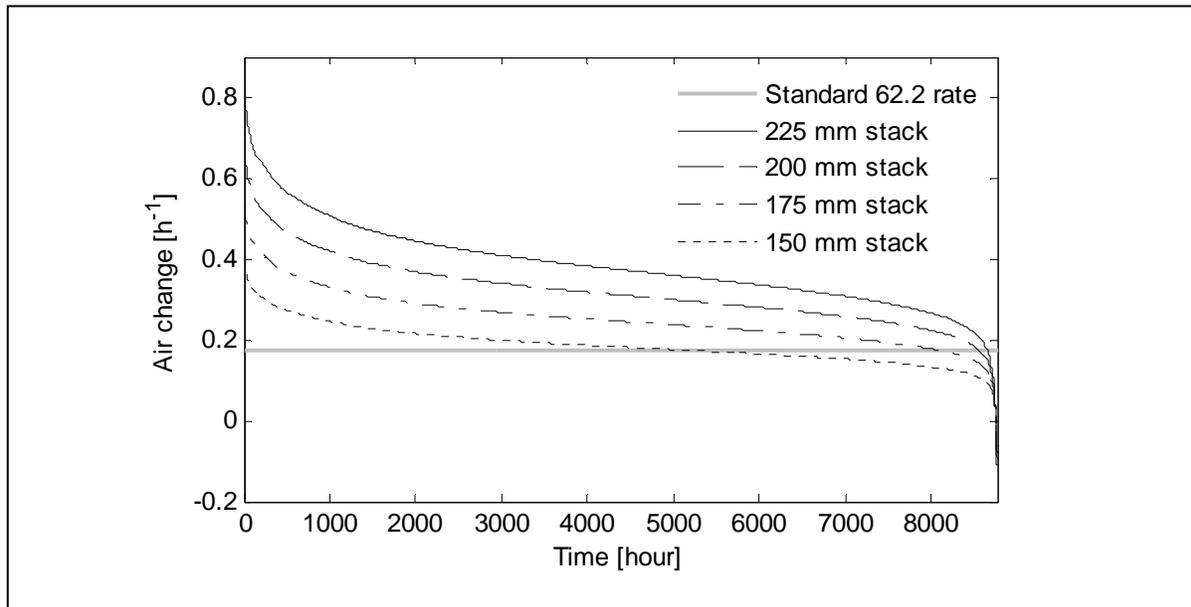
To make the results of this study fairly broadly applicable to many homes, the size, geometry and other performance aspects of the evaluated residence were typical of new homes in the U.S. A single-story house of 195 m² (2100ft²) based on the prototype C house in the

Residential Alternative Calculation Manual (California Energy Commission 2008a) was used. The performance characteristics of the house were as prescribed in component package D of the Residential Compliance Manual (California Energy Commission 2008b) for a house with wood-framed walls and slab on grade. Based on empirical data from new single-family detached homes in California (Offerman et al. 2007) the Specific Leakage Area (SLA) of the house was set to 2.7. This is close to the U.S. nationwide average reported earlier by Sherman and Matson (2002) whose results showed an SLA of 3 for new homes. This leakage was distributed with 35% in the walls, 50% in the ceiling and 15% at floor level – which is appropriate for single-story slab-on-grade construction. The simulations were performed for four California climates: cold, temperate, warm and desert, which are representative of Mt. Shasta, Oakland, Sacramento and El Centro, respectively. Weather data files used in California State Energy Code Compliance calculations were used as input for the simulations. The house was located in an urban area and wind speeds were adjusted to account for local wind shelter.

The indoor air quality metric used in this study to prove equivalent air quality is relative dose. Dose represents people's average exposure to pollutants. The exposure and thus dose is assumed to be linearly proportional to the pollutant concentration. A steady-state emission rate from a source was assumed throughout the year. The relative dose is the ratio of the dose for the passive stack system to that of a continuously operated mechanical ventilation system. The other infiltration air flows for the house were not included in the dose calculations: only the whole-house ventilation system flow rates are used because we want to show equivalency to ASHRAE 62.2. In this study a 24-hour moving average of relative dose was used to calculate relative dose because most ventilation requirements, weather variability and occupant issues are on daily cycles.

For this study, a passive stack was designed with the intent to provide as much as possible of the ventilation required by Standard 62.2. To achieve this, the stack was “oversized” to allow for higher air flows at low driving pressures. The minimum ventilation rate required by ASHRAE 62.2 for the house is $0.024 \text{ m}^3/\text{s}$ or 0.18 air changes per hour. The passive stack was sized so that for most of the year it provided this ventilation rate. To select an appropriate stack size, yearly simulations of the ventilation provided by a 3 m high stack with diameters ranging from 150 to 225 mm were investigated for the temperate climate. The passive stack's air flow coefficient was based on a combination of laboratory tests (Walker, Wilson and Sherman 1998) and standard hydrodynamic calculations (ASHRAE 2009). For example, the 200mm stack had a flow coefficient of $0.038 \text{ m}^3/\text{sPa}$, which equals 38 % of the total house leakage. Figure 1 summarizes the hourly average air change rates in the stack by showing the cumulative time each stack reaches a given air flow rate. A positive flow implies flow out of the house and a negative flow implies flow into the house (this happens when it is cooler indoors than outdoors during calm and hot conditions when the air conditioning is operating). A stack size of 200 mm ventilated the house at a rate higher than the ASHRAE 62.2 rate 98 % of the year and is therefore an appropriate size for our purposes.

Figure 1: Cumulated hourly average air change rates during a year.



A smaller or larger house would require a smaller or larger stack. Table 1 contains a simple rule of thumb for scaling the passive stack diameter with house size (floor area). Due to typical space limitations in residential construction it may be necessary to restrict stack diameters to a maximum of, say, 8 in. (200 mm). In which case, larger houses will require multiple stacks. The multiple stacks also make sense from the point of view of extracting pollutants from multiple sources – e.g., from all bathrooms.

Table 1: Passive stack diameters scaling with house size

Floor area [ft ²]	Stack diameter	Floor area [m ²]	Stack diameter
<1000	4 in.	<100	100 mm
1000-1500	6 in.	100-150	150 mm
1500-2000	8 in.	150-200	200 mm
2000-3000	2x6 in.	200-300	2x150 mm
>3000	2x8 in.	>300	2x200 mm

To avoid excess consumption of energy for heating and cooling the passive stack was equipped with a flow controller that was capable of limiting the flow in the stack when over-ventilation occurred. The flow controller limited the maximum stack flow to the ASHRAE 62.2 rate. Depending on stack size and local weather it may be desirable to limit the flow above the ASHRAE 62.2 rate to compensate for times of low air flow in the passive stack. Suitable low pressure air flow controllers are currently not available but could be developed from existing products such as those from TSI (Trust Science Innovation - www.tsi.com), American Aldes or TNO (TNO is the Dutch acronym for the Netherlands Organization for Applied Scientific Research - www.tno.nl) that are normally used in mechanical ventilation systems to ensure uniform air flows from multiple inlets and over wide ranges of static pressure differences. Axley (2001) and DeGids (1997) give more details on air flow controllers.

Energy consumption and indoor air quality for the following three cases were examined:

- Fully open stack
- Stack flow limited to 100% of ASHRAE standard 62.2 rate
- Stack flow limited to 125% of ASHRAE standard 62.2 rate

The energy consumed by the heating (natural gas) and cooling systems was determined by the simulations. The heating and cooling systems operated so as to meet the fixed thermostat schedule based on the energy balance of the home that included the ventilation air flows. The energy associated with the ventilation air flows depends on the air flow rate and the coincident indoor to outdoor temperature difference – hence the need for detailed year-long simulations. As with the relative dose for indoor air quality equivalence, the energy consumption of the passive systems was compared to that for the continuously operated mechanical system. For this study, the mechanical exhaust system was equipped with an ASHRAE 62.2 compliant (i.e., a quiet) fan with a fan power of 11.8 W based on ratings in the Home Ventilating Institute directory (HVI 2009). This is typical power consumption for an ASHRAE 62.2 compliant fan because ASHRAE 62.2 requires the use of quiet (<1 sone) fans which tend to be efficient. A more typical exhaust fan would use about 50 W. Similarly an HRV sized to produce the same average airflow would also use about 50 W on average. A common HRV installation also uses the central forced air system blower to distribute ventilation air. These blowers typically consume 500 W to 700 W (Walker 2008). Because HRV airflows are typically three times the ASHRAE 62.2 minimum requirements they only need to operate one third of the time. This leads to an average energy consumption of about 200W for an HRV. This fan power consumption is obviously critical when estimating energy savings so both low and high power consumption will be examined in our analysis.

Results

The annual average indoor air quality performance represented by relative dose and the yearly energy consumption of the single-story house are given in table 2. The change in energy consumption is compared to the reference system with continuous mechanical exhaust ventilation. Annual cost reductions were calculated based on electricity and heating (natural gas) prices of \$0.18/kWh and \$0.06/kWh respectively

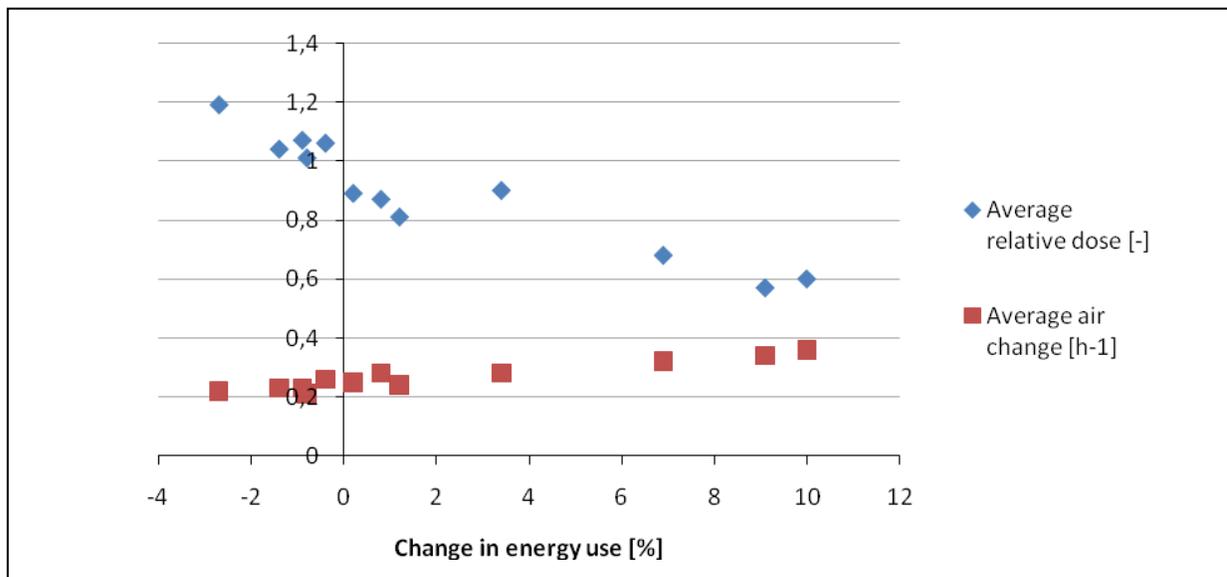
Table 2: Annual performance of the passive stack systems

Climate and stack type	Average air change [h ⁻¹]	Average relative dose [-]	Electricity [kWh]	Heating [kWh]	Change in energy use [%]	Change in annual cost [%]
COLD climate						
Open stack	0.36	0.60	1056	30563	10.0%	8.7%
Stack flow ≤ 100% of 62.2 rate	0.26	1.06	1030	27606	-0.4%	-1.1%
Stack flow ≤ 125% of 62.2 rate	0.28	0.87	1030	27939	0.8%	0.0%
TEMPERATE climate						

Open stack	0.34	0.57	301	12834	9.1%	7.2%
Stack flow \leq 100% of 62.2 rate	0.21	1.01	285	11664	-0.8%	-2.3%
Stack flow \leq 125% of 62.2 rate	0.24	0.81	284	11903	1.2%	-0.5%
WARM climate						
Open stack	0.32	0.68	1570	13654	6.9%	3.4%
Stack flow \leq 100% of 62.2 rate	0.23	1.07	1640	12466	-0.9%	-2.1%
Stack flow \leq 125% of 62.2 rate	0.25	0.89	1616	12648	0.2%	-1.5%
DESERT climate						
Open stack	0.28	0.90	5409	4023	3.4%	-0.7%
Stack flow \leq 100% of 62.2 rate	0.22	1.19	5385	3482	-2.7%	-3.6%
Stack flow \leq 125% of 62.2 rate	0.23	1.04	5399	3587	-1.4%	-2.9%

The average air changes and relative doses given in table 2 are plotted as a function of the change in energy use in figure 2. The figure clearly shows that the use of energy increases as the home is ventilated more, but also that more ventilation results in a lower relative dose, i.e., better air quality.

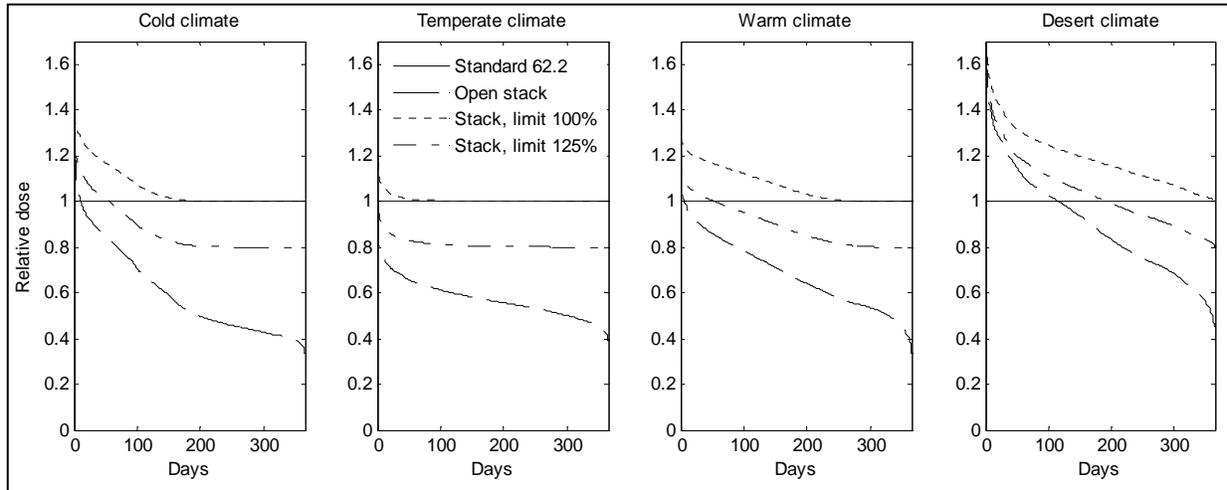
Figure 2: Average air change and relative dose as a function of the change in energy use



The changes in energy use are much smaller than the changes in relative dose. The relative dose ranges from approximately 0.6 to 1.2 whereas the change in energy use ranges from -3% to 10%. This implies that we could specify considerably better indoor air quality (lower relative dose) for small changes in energy use. The variability in passive stack air flows leads to either over-ventilation and associated energy penalty or under-ventilation and poor air quality. This tradeoff needs to be optimized. The ideal solution is to use a passive stack that provides the same or better relative dose (≤ 1) with no or negative change in energy use. The results in table 2 show that a reasonably sized passive stack can provide indoor air quality equivalency in most cases, and that the maximum flow control is successful in controlling over-ventilation. The climate variability in relative dose indicates that optimized stack sizes may need to include a climate consideration. In addition to the annual values of relative dose, it is necessary to look at

the range of relative dose. Although the equivalence to standard 62.2 is shown by annual averages, it would be a good idea to avoid systems that sometimes substantially under-ventilate resulting in high relative dose levels – even if they are for short periods of time. For example, if a particular stack size or control methods gives equivalent energy and indoor air quality performance, a designer may want to base selection and design on reducing this peak dose level. To examine range and distribution of the yearly averaged indoor air quality results given in table 2 the cumulative time each of the passive stack systems reached a certain relative dose during a year is plotted in figure 3.

Figure 3: Cumulated daily average of relative dose during a year



The relative dose of the fully open stack varies least in the temperate climate and most in the desert climate. This implies that stack flows are most stable in the temperate climate. The effect of limiting the flow in the passive stack to 100% and 125% of the ASHRAE 62.2 rate appears clearly in the cold, temperate and warm climates as the lower boundary of the relative dose approaches values of 1 and 0.8 respectively. This tendency is not seen in the desert climate because the ventilation provided by the stack barely reaches these rates. The desert climate has much more time when weather conditions result in small driving forces for natural ventilation and therefore there are more times with higher relative dose. Combined with the annual results – this indicates that a bigger stack would be more ideal in the desert and that passive stacks may not be practical in climates with long periods of low driving forces.

Discussion

Systems with a flow controller which limits the flow to 100% of the required rate in the cold, temperate and warm climate are very close (maximum difference of 7%) to achieving equivalent indoor air quality on an annual basis. , whereas a A flow controller limiting the flow to 125% of the required level is needed in the desert climate to get within 5% of the equivalent indoor air quality. Whether these departures from exactly equivalent dose are significant are debatable given uncertainty in determining indoor pollutant generation rates, natural ventilation effects, etc.

Both energy and cost were examined because energy is relevant for public policy decisions addressing such issues as global climate change, resource conservation and outdoor air quality, whereas the cost may be more relevant for building occupants from an economic perspective. The results presented here illustrate how energy and cost do not necessarily scale directly – depending on switching between different fuels (in this case natural gas and electricity) that have different costs. The 200 mm passive stack without a flow controller results in an average relative dose significantly below 1 for all climates hence the house is on average ventilated more than required per ASHRAE 62.2. The cost of the improved air quality is energy consumption increases of 3 to 10%. The increased energy consumption is reflected in the annual cost; however, the increments in cost are lower due to the lower price of heating energy compared to electricity. If we restrict the analysis to results with the close to the same relative dose (this is the passive stack restricted to 100% of the ASHRAE 62.2 flow rate – except in the hot climate) then we see small energy savings of 0.4% to 0.9%. These savings are the effect of exploiting natural driving forces for transportation of the air.

Overall, these results indicate that the flow controller is a good idea for limiting over-ventilation and increased energy use, that energy savings are small because fan power use is low in the mechanically ventilated case, and that there are only small energy penalties associated with substantial reductions in dose. The relationship between relative dose and energy use shows that relative dose changes about 6 times faster than the fractional change in energy, independent of climate. The ratio is about 6:1 so a 5% energy use increase yields a 30% reduction in average relative dose.

The flow controller which limited the flow to 125% of the required rate proved to be over dimensioned with regard to providing an air quality similar to that of the continuously operated ASHRAE 62.2 system. The intended purpose of over dimensioning of the flow controller to compensate for periods with low stack flows only served its purpose in the desert climate. In terms of dealing with climate variation there are two possible approaches. Either introduce a stack size variation with climate, or recommend one stack for all climates and use an “over-ventilation” controller. This selection is likely to be limited by other considerations, such as the space available for the passive stack. Lastly, if space restrictions limit the size of passive stack to be smaller than our recommended values then it might be possible to use a over-ventilation flow controller set to a higher limit to allow for higher peak ventilation rates. However, this is unlikely to be a preferred method because there will be more days of the year when the home is under-ventilated even if the average relative dose is the same that could lead to too many occurrences of unacceptable indoor conditions. This is an issue for future work.

The changes in energy consumption and in the annual cost were calculated with respect to a reference system equipped with a very energy efficient fan (as required by ASHRAE 62.2 indirectly due to its sound level restrictions). A less efficient fan more typical of what is widespread used by builders and contractors (or an HRV not linked to the central forced air system) that would use about 50W would not change the energy used to condition the air; however, the energy consumption and annual cost would change in favor of the passive system. A fan of 50W would increase the electric energy consumption by 334kWh per year resulting in energy savings of 1.5 to 4.9% for the systems with a relative dose of approximately 1. Expanding this analysis to HRV's linked to central forced air system operation results in even greater fan power savings. In addition to the 50W used by the HRV there is an additional 200W of central forced air system blower power leading to 2100kWh of fan power savings that could lead to

energy savings approaching 20%. These savings relative to an HRV are offset by the reductions in energy used to condition the ventilation air - typically 60-70% savings.

The simple stack sizing approach used in this study gave good results in terms of relative dose and limited excess energy use when equipped with an air flow controller. However, this was for a single stack height appropriate for a single-story building. Because stack effect depends on the height of the stack it is reasonable to assume that the stack diameter could be reduced for a taller stack used in a two or three-story home. This requires further investigation.

Conclusion

Passive stack ventilation in residences can provide acceptable indoor air quality per ASHRAE 62.2 provided the vents are sized appropriately. If a passive stack is to be used, we recommend using a passive stack large enough to provide some minimum ventilation level during periods of low driving forces while employing a flow controller to limit the highest air flows. There are small energy savings that can be realized due to not having to operate a fan - on the order of 1% of space conditioning energy.

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