Performance of a CO$_2$-based demand controlled dual core energy recovery ventilation system for northern housing experiencing varying occupancy

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Abstract. Indoor air quality and health are major areas of concern in northern and remote communities where homes experience varying occupancy, often overcrowding and are influenced by ventilation. Heat/energy recovery ventilators installed in the north are selected to provide required minimum ventilation rate set by ventilation standards (ASHRAE 62.2, etc.). Northern overcrowded homes become under-ventilated, leading to deteriorated IAQ, mold and health-related problems. This paper presents results from a side-by-side testing of a CO$_2$-based demand-controlled ERV versus a constant air flows ERV, using twin houses with simulated occupancies. The control strategy was based on the difference in CO$_2$-concentration between exhaust/return air from the house and outdoor air. The implemented strategy based on a CO$_2$ sensor network connected with an ERV continuously exhausting stale air from kitchen and bathrooms was simple and efficient in adjusting ventilation rate based on occupancy rate. The CO$_2$-based demand-controlled ERV provided a much better control of indoor CO$_2$ concentrations in the main floor and master bedroom, and with lower CO$_2$ concentrations in bedrooms during night time, compared to the reference house with concentrations exceeding 2000 ppm. However, the CO$_2$-based demand-controlled ERV had higher power consumption than conventional ERV with constant air flows.

1 Introduction

In order to provide a healthy indoor environment for building occupants, most jurisdictions prescribe residential ventilation rates based on the size of the space and the number of anticipated occupants. These ventilation rates are intended “to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects” [1, 2]. As interest in energy conservation grows, balanced supply and exhaust systems are becoming increasingly popular in cold climates because they allow for waste heat to be recaptured from exhaust air. Balanced residential ventilation systems such as heat/energy recovery ventilation systems also allow for pre-filtration of supply air and prevent depressurization, which can have negative effects on indoor air quality [3]. ASHRAE ventilation standard [1] and the National Building Code [4] set the required (constant) ventilation rate, calculated on the basis of fixed liveable floor area and fixed number of bedrooms or people. HRV/ERV units are selected to meet the required ventilation and their selection is based on the calculated minimum ventilation rate. Canada’s northern and remote communities face an acute overcrowding housing crisis which threatens their health and safety. In Nunavik alone, over half of the Inuit families live in overcrowded housing, and in too many communities, up to 15 people, including young children, live in small three bedroom units. Overcrowding continues to have serious public health repercussions throughout Inuit territories. High levels of respiratory infections among Inuit children, such as chronic lung disease developing after lower respiratory tract infections, are also linked to crowding and poorly ventilated homes [5]. For northern housing experiencing varying occupancy (often overcrowding) and indoor conditions (high indoor activities), to ensure good indoor air and environment quality, finding optimal mechanical ventilation solution is the concern in northern residential well-insulated dwellings. HRVs/ERVs installed in northern communities offer constant airflows and constant ventilation rate that is often not adequate for varying and high occupancy situations common in northern and remote communities, leading to deteriorated indoor air quality (IAQ). To better address IAQ under varying occupancy and indoor environment conditions seen in northern and remote communities, ventilation needs to become smarter. The key of the smart heat/energy recovery ventilation concept is to use controls to ventilate more at times

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when it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. The fundamental goal of this concept is to adjust ventilation provision of outdoor air) according to indoor needs and provide required ventilation to maintain a comfortable and healthy indoor environment [6]. In this study, a simple strategy for residential demand-controlled heat/energy recovery ventilation has been investigated through the assessment of the performance of a CO₂-based residential dual core ERV system to better control the indoor CO₂ concentrations when a house is experiencing varying occupancy or overcrowding. The control is based on the measured difference in CO₂-concentration between the return air from indoor to the ERV and the outdoor air. The main objective of this paper is to evaluate the effect of CO₂-based demand-controlled ventilation applied to an energy recovery ventilation system on: zonal indoor CO₂ concentrations and control, and the power consumption of the demand-controlled ERV.

1. Method

The Canadian Centre for Housing Technology’s (CHHT) twin houses were used for the comparative side-by-side testing between a CO₂-based demand-controlled dual core ERV (installed in the Test House) and a conventional single core ERV with constant air flows (installed in the Reference House). The presence of people is based on the difference in CO₂ concentration between the ERV’s exhaust air and outdoor air intake. The CO₂-based DCV strategy was implemented to the dual core ERV installed in the Test House. CCHT Houses are unoccupied, automated CO₂ dosing systems were designed and deployed in both houses to simulate variable occupancies through automated zonal controlled CO₂ dosing strategy. The concentration level of indoor carbon dioxide is a good indicator of the occupancy rate while protecting the personal privacy of dwelling residents. CO₂ sensors are easy and relatively cheap to install compared to other techniques for occupant detection.

1.1 Control strategy

The implemented control strategy was based on the CO₂ concentration difference between outdoor and ERV’s exhaust air from indoor, and the difference in CO₂ concentration was used to determine occupancy. Assuming return air from indoor CO₂ concentration equal to the outdoor concentration when the space is unoccupied (time 0), and with development of a difference in CO₂ concentration in situations when one person enters the bedroom at up to 4 flow rates. This ventilation strategy switches the air flows between up to 4 flow rates controlled by the speed of the fans - supply air flow controlled by the speed of the supply fan and the exhaust air flow controlled by the speed of the exhaust fan of the ERV. The low air flow is used for an unoccupied house and it is adjusted (demand-controlled) for increased occupancy rates. This control strategy was based only on measurements in the ERV unit that control the speed of the supply and exhaust fans, to make the system less expensive. A threshold for CO₂ concentration between 100 and 200 ppm is suitable to ensure that the system switches to the high ventilation rate shortly after people enter the bedroom [6]. The proposed CO₂ sensor network or system consists of CO₂ sensors and a central computer. Measurement results at the intake and the return to the ERV are transmitted to the central control computer via wired communication. The CO₂ sensors have a wide measuring range of 0-5000 ppm. Their output is an analog voltage, which linearly varies with sensed CO₂ level. As a result, the output voltage of this CO₂ sensor precisely indicates ambient CO₂ level. The output voltage of a CO₂ sensor should respond to timing-varying space occupancy (varying indoor CO₂ concentration).

2. 1.2 Side-by-side testing

The side-by-side testing methodology using the CCHT twin houses enabled a whole house evaluation of the impact of the CO₂-based demand-controlled dual core ERV system. The side-by-side testing involved first benchmarking the houses for a set of operating conditions and simulated occupancy, using existing high efficiency single core ERVs originally installed in each house, followed by installing the dual core ERV unit in the Test House basement and making no other modifications to the house, then programming the dual core unit to match the single core ERV supply and exhaust airflow in the Reference House, and finally monitoring the performance of the two houses side-by-side for four weeks during winter. The side-by-side testing – dual core ERV versus single core ERV – was done with continuous mixing, 100% central fan operation at low speed when there is no call for heating. ERVs are partially dedicated systems with a direct connection of the supply air stream to the air handler air return, and stale air drawn from kitchen and bathrooms, as shown in Figure 1.

Fig. 1. ERV in conjunction with forced air system.

ERVs were instrumented with temperature and humidity sensors, and two air flow meters to monitor the
supply and exhaust airstreams. The dual core ERV has a dedicated DAS and laptop, with a program that controls the change in the relative fan speed to adjust the supply and exhaust air flows. Indoor conditions in terms of temperature, relative humidity and CO₂ concentration were measured in both houses and in zones with simulated occupancy; main floor (MF), master bedroom (MBR), bedroom 2 (BR2) and bedroom 4 (BR4), using Hobas data loggers.

### 1.3 Testing procedure

Measurements have been performed over three periods with respectively simulated occupancy of two adults + two children, four adults + four children and six adults + four children. The ventilation rate required by the North American ventilation standard (ASHRAE 2017) is 0.3 cfm (0.15 L/s) per m² required by the building plus 7.5 cfm (3.5 L/s) per person (number of bedroom + 1) required by people. Testing have been done for normal operation of the single core ERV in the Reference House with a constant air flows of 85 cfm (40 L/s) and the dual core ERV in the Test House set at its minimum air flows of 75 cfm (35 L/s) and demand-controlled to up 150 cfm (71 L/s) based on the difference in CO₂ concentration between return air from indoor to the ERV and outdoor, as shown in Table 1.

#### Table 1. Fan’s relative speed for control strategy.

<table>
<thead>
<tr>
<th>Speed</th>
<th>SA Fan (%)</th>
<th>RA Fan (%)</th>
<th>CO₂ threshold (ppm)</th>
<th>Flow (L/s) [cfm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47</td>
<td>40</td>
<td>&lt; 150</td>
<td>35 [75]</td>
</tr>
<tr>
<td>2</td>
<td>58</td>
<td>48</td>
<td>&gt; 150</td>
<td>47 [100]</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>57</td>
<td>&gt; 300</td>
<td>59 [125]</td>
</tr>
<tr>
<td>4</td>
<td>79</td>
<td>63</td>
<td>&gt; 450</td>
<td>71 [150]</td>
</tr>
</tbody>
</table>

Simulated occupancies were achieved in designated zones shown in Figure 2; main floor [M] (open area with kitchen, dining/living areas and bathroom), master bedroom [1] on the second floor (with automated door and a master bathroom with door open), bedroom 2 [2] and bedroom 4 [4] on the second floor with automated doors. Both houses had bedroom 3 [3] on the second floor with door open and no simulated occupancy, and a bathroom with open door.

The twin houses were unoccupied and required simulation occupancy achieved by automated CO₂ dosing systems. Two automated CO₂ dosing systems were designed and used to simulate identical zonal occupancies in both houses. The dosing systems were designed with a 4-channel stand-alone microprocessor-based configurable digital indicator and power supply capable of interfacing directly to analog mass flow controllers (MFCs). The instrument configuration and control was done via the RS-232C interface. The MFC is an all-metal mass flow meter designed to measure the flow of CO₂ with accuracies of 1% of full scale and 1% of reading, respectively, and automated CO₂ dosing systems were controlled via dedicated laptop.

A varying 24 hours of zonal simulated occupancies were performed in both houses from 0:00 to 24:00 as presented in Table 2. Adult bedroom with one male and one female sleeping in the bedroom is simulated by a CO₂ dosing flow of 0.216 L/min, child’s bedroom with one male and one female sleeping in the bedroom is simulated by a CO₂ dosing flow of 0.150 L/min and a residence (common areas such as dining room, living room, etc.) with two adults (one male and one female) and two children (one male and one female) is simulated by a CO₂ dosing flow of 0.240 L/min [7].

#### Table 2. Fan’s relative speed for control strategy.

<table>
<thead>
<tr>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Start Time (Duration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBR</td>
<td>2 adults</td>
<td>2 adults</td>
<td>2 adults</td>
<td>0:00 (6 hrs 45 min)</td>
</tr>
<tr>
<td>BR2</td>
<td>0</td>
<td>2 adults</td>
<td>2 adults</td>
<td>0:00 (6 hrs 45 min)</td>
</tr>
<tr>
<td>BR4</td>
<td>2 children</td>
<td>4 children</td>
<td>2 adults + 2 children</td>
<td>0:00 (6 hrs 45 min)</td>
</tr>
</tbody>
</table>

- **Morning/Breakfast**
  - MF: 2 adults + 2 children, 4 adults + 4 children, 6 adults + 4 children, duration 7:00 (1 hr)
  - Noon/Lunch: 2 adults + 2 children, 4 adults + 4 children, 6 adults + 4 children, duration 12:00 (1 hr)
- **Evening**
  - MF: 2 adults + 2 children, 4 adults + 4 children, 6 adults + 4 children, duration 17:30 (3 hrs 30 min)
  - MBR: 2 adults, 4 adults, 6 adults, duration 21:00 (2 hrs)
  - BR2: 2 adults, duration 23:00 (1 hr)
  - BR4: 2 adults, duration 23:00 (1 hr)

Fig. 2. Designated zones for simulated occupancy.
2 Results and discussion

The difference in CO₂-concentrations between the exhaust air and the outdoor air was used to determine occupancy with the assumption that for a difference in CO₂-concentrations below 150 ppm between the exhaust air from indoor and outdoor air, the house is empty (no presence of people). Results are presented as the difference in CO₂-concentration between the extracted air and outdoor air and the relative supply and exhaust fans speeds. Figure 3 shows the typical 24-hours demand-controlled ventilation in the test house for Period 3 with occupancy of 6 adults and 4 children. Results are presented as the difference in CO₂-concentration between extracted air and outdoor air and the relative supply and exhaust ERV fans speeds. The plots show clearly that the high ventilation rate is active when one of the threshold values are exceeded.

![Fig. 3. Difference in CO₂ concentration and relative fan’s speeds for period 3.](image)

The difference in CO₂-concentration between extracted air and outdoor air exceeded the three thresholds of 150 ppm, 300 ppm and 450 ppm during period 3, and the CO₂-based demand-controlled dual core ERV fans switched between speed 1 and speed 4. Table 3 shows the fraction of time during measured periods 1, 2 and 3 the fans were on speed 1, speed 2, speed 3 and speed 4.

<table>
<thead>
<tr>
<th>Period</th>
<th>Speed 1</th>
<th>Speed 2</th>
<th>Speed 3</th>
<th>Speed 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40%</td>
<td>60%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>10%</td>
<td>39%</td>
<td>50%</td>
<td>1%</td>
</tr>
<tr>
<td>3</td>
<td>2%</td>
<td>29%</td>
<td>50%</td>
<td>19%</td>
</tr>
</tbody>
</table>

During Period 1, the CO₂-based DC dual core ERV was running 40% of the time on speed 1 and 60% of the time on speed 2. In this case, the ventilation in the Test House was running with the low ventilation rate of 35 L/s [75 cfm] 40% of the time. With increased occupancy during Period 2, the supply and exhaust fans had to switch to higher speeds. The CO₂-based DC dual core ERV was running 10% of the time on speed 1, 39% of the time on speed 2, 50% of the time on speed 3 and 1% of the time on speed 4. With the highest occupancy rate of 6 adults and 4 children, the DC dual core ERV was running only 2% of the time on low speed 1, 29% of the time on speed 2, 50% of the time on speed 3 and on the highest speed 4 19% of the time.

Measurements of CO₂ concentrations were undertaken in four zones with simulated occupancy: main floor (MF), bedroom 2 (BR2), bedroom 4 (BR4) and master bedroom (MBR). Figure 4 shows a daily measured CO₂ concentration in zones with simulated occupancies in the Test House equipped with a CO₂-based demand-controlled ERV during period 3. Figure 5 shows a daily measured CO₂ concentration in zones with simulated occupancies in the Reference House equipped with a conventional constant air flows ERV, during period 3. The plots of the variation in zonal CO₂ concentrations were characterized by four indoor events; [1] bedtime with bedroom’s door closed, [2] breakfast time on the main floor, [3] lunch time on the main floor and [4] family time including dinner time on the main floor.

![Fig. 4. Daily time variations of zonal CO₂ concentrations in Test House during Period 3.](image)

![Fig. 5. Daily time variations of zonal CO₂ concentrations in Reference House during Period 3.](image)

The highest CO₂ concentrations were measured in bedrooms during bedtime, with bedroom’s door closed, exceeding 1200 ppm. This is a result of high people load in the bedroom with occupancy two adults + two children sleeping in master bedroom, two adults sleeping in bedroom 2 and two adults + two children sleeping in bedroom 4. Bedroom 4 with occupancy of two adults + two children sleeping during Period 3 had the highest CO₂ concentrations during night time reaching 1800 ppm in the Test House with demand-controlled ERV and much higher concentration concentrations up to 2800 ppm in the Reference House with constant air flow ERV. Master bedroom with same occupancy as bedroom 4 of 2 adults and 2 children sleeping in the room had much lower CO₂ concentrations, due to the continuous extraction of air from the master bathroom by the ERV and with master bathroom door open to the master bedroom. Stale air extracted from bedroom 4 was not directly extracted to
outdoor, but recirculated in the house through the furnace were it was conditioned and filtered. CO₂ concentrations in master bedroom did not exceed 1200 ppm in the Test House during bedtime and reached 1500 ppm in the Reference House. Bedroom 2 with two adults sleeping in the room were below 1300 ppm in the Test House during night time and below 1450 ppm in the Reference House. The main floor area had higher CO₂ concentrations exceeding 1000 ppm in the morning when the whole family was having breakfast, at lunch time and in the evening between 6 and 11 PM. During daytime the house is unoccupied and the CO₂ concentration drops to values close to the outdoor concentration.

Figure 6 and Figure 7 show respectively the fraction of time the measured CO₂ concentration in master bedroom and bedroom 4 exceeded the threshold of 1000 ppm during Period 1 with occupancy of two adults sleeping in the master bedroom and two children sleeping in bedroom 4, a total house occupancy of 2 adults + 2 children. Both houses had CO₂ concentrations in master bedroom 100% of the time below 1000 ppm, due to the continuous exhaust from master bathroom with door open to master bedroom by the ERV. However, measured CO₂ concentrations in bedroom 4 with stale air recirculated in the house through the Furnace for conditioning and filtration and not exhausted directly to outdoor has exceeded 1000 ppm 20% of the time. All zones had CO₂ concentrations bellow 1200 ppm during Period 1 with a total occupancy of 2 adults + 2 children, two adults sleeping in master bedroom and two children sleeping in bedroom 4.

Figure 8 and Figure 9 show respectively the fraction of time the measured CO₂ concentration in master bedroom and bedroom 4 exceeded the threshold of 1000 ppm during Period 2 with occupancy of two adults sleeping in the master bedroom and four children sleeping in bedroom 4, and total house occupancy of 4 adults + 4 children (two adults sleeping in bedroom 2). With higher occupancy during period 2, Figure 8 shows that measured CO₂ concentration in the master bedroom exceeded 1000 ppm, with 89% of the time below 1000 ppm in the Test House with CO₂-based DC ERV and 70% of the time in the Reference House with constant air flows ERV, and master bedroom measured concentrations were below 1200 ppm in both houses. However, Bedroom 4 had much higher CO₂ concentrations than master bedroom as shown in Figure 9, with concentrations 34% of time higher than 1000 ppm in the Test House compared to 39% of the time in the Reference house. Concentrations exceeded 1800 ppm 3% of the time in the Test House compared to 12% in the Reference House.

Figure 10 and Figure 11 show respectively the fraction of time the measured CO₂ concentration in master bedroom and bedroom 4 exceeded the threshold of 1000 ppm during Period 3 with occupancy of two adults and two children sleeping in the master bedroom and bedroom 4, and total house occupancy of 6 adults + 4 children (two adults sleeping in bedroom 2). With the highest occupancy during Period 3, Figure 10 shows that master bedroom had CO₂ concentrations 40% of the time higher than 1000 ppm in the Test House and 52% of the time in the Reference House. Master bedroom had
much higher concentrations during Period 3, exceeding 1400 ppm 1% of the time in the Test House compared to 25% in the Reference House. Figure 11 shows that bedroom 4 with higher occupancy of two adults + 2 children sleeping in the room and without direct exhaust of stale to outdoor by the ERV, had again much higher concentrations than during Period 2 and master bedroom during Period 3. Measured concentrations exceeded 1000 ppm were 45% of time higher than 1000 ppm in the Test House with DC ERV compared to 66% in the Reference House with constant air flows ERV, 30% of the time higher than 1400 ppm in the Test House compared to 37% in the Reference House, and 3% of the time higher than 2000 ppm in the Test House compared to 28% in the Reference House.

![Image](https://example.com/image1.png)

Fig. 10. Fraction of time CO2 concentrations in MBR during Period 3.

![Image](https://example.com/image2.png)

Fig. 11. Fraction of time CO2 concentrations in BR4 during Period 3.

The main floor with continuous exhaust of stale from kitchen and one bathroom had CO2 concentrations 100% of the time below 1000 ppm during Period 1 in both houses with two adults + 2 children. During Period 2 with occupancy of 4 adults + 4 children, measured CO2 concentrations were 3% of the time higher than 1000 ppm in the Test House compared to 11% in the Reference House and without exceeding 1200 ppm. During Period 3 with occupancy of 6 adults + 4 children, measured CO2 concentrations were 20% of the time higher than 1000 ppm in the Test House compared to 60% in the Reference House and were below 1200 ppm.

Overall results from the first phase of this research showed that a simple CO2-based energy recovery ventilation system was more effective in controlling indoor CO2 concentrations in zones with continuous and direct exhaust of stale air to outdoor such as main floor and master bedroom than zones (bedrooms with closed door during bedtime) relying on dilution, return of stale air from bedroom through the furnace and recirculated in the house. A house with a simple demand-controlled strategy implemented to an ERV with continuous exhaust from kitchen and bathrooms improved significantly the control of indoor CO2 concentrations in a house experiencing high occupancies and specifically in bedrooms with closed doors during bedtime.

Table 4 shows the ERV’s power consumption. As the CO2 concentration in the test house increases, made the CO2-based DC ERV operate at higher fan’s speeds. As expected, this caused operation time at high speeds and higher energy consumption of the ERV in the test house, increased by 53% between period 1 and period 2 (high occupancy), and by 82% between period 1 and period 3.

<table>
<thead>
<tr>
<th>Period</th>
<th>Test House (kWh)</th>
<th>Reference House (kWh)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.877</td>
<td>0.904</td>
<td>-2.9%</td>
</tr>
<tr>
<td>2</td>
<td>1.343 (+53%)</td>
<td>0.904</td>
<td>+48.6%</td>
</tr>
<tr>
<td>3</td>
<td>1.599 (+82%)</td>
<td>0.895</td>
<td>+78.7%</td>
</tr>
</tbody>
</table>

3 Conclusion

Results revealed that a simple control strategy based on sensing CO2 concentrations in the outdoor air and a return air from indoor to the ERV can be effective in controlling the CO2 concentration in the entire house. A house with a CO2-based demand-controlled ERV had a much better control of indoor CO2 concentrations during high occupancy and bedtime in rooms. A CO2-based demand-controlled energy recovery ventilation was more effective for zones with direct and continuous extraction of stale air to outdoor (such as main floor and master bedroom), but less effective for bedrooms with doors closed during sleeping time of the residents. Bedrooms experienced levels of CO2 concentrations exceeding 1600 ppm during bedtime. As expected, demand-controlled ventilation strategy had a negative impact on the CO2-based dual core ERV power consumption that increased by up to 82%.

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References


