2_C26

Applicability of a CO_2-based Demand Controlled Energy Recovery Ventilator to a Test Bedroom with Varying Simulated Occupancy

Boualem Ouazia, PhD
[ASHRAE Member]

Chantal Arsenault

Mark Vuotari, PE

Gang Nong, PE

Daniel Sanders, PE

ABSTRACT

Indoor air quality is a major area of concern in northern housing and could be influenced by ventilation. The required ventilation rate set by North American ventilation standards (ASHRAE 62.2, CSA-F326) is calculated on the basis of fixed floor area and number of bedrooms or people. The heat/energy recovery ventilators (HRV/ERV) on the market offer constant airflows and are selected to meet the required ventilation. The ventilation rate could be too low for northern housing experiencing varying indoor conditions and occupancy, producing higher indoor concentrations of pollutants (RH, CO_2, etc.) that need to be controlled. This paper presents results from an experimental assessment of a CO_2-based demand-controlled ERV unit to a test bedroom with varying simulated occupancy. Three strategies for demand-controlled energy recovery ventilation were implemented in a test bedroom with varying occupancy of up to four adults sleeping in the bedroom. The implemented strategies are based on sensing CO_2-concentration in the indoor air and in both the exhaust and supply air. The CO_2-concentraion was used to ensure adequate ventilation during varying occupancy in the test bedroom. The ventilation rate can be switched between four flow rates or between two flow rates. The control strategy based on switching the air flow between four levels (fan speed switched between four relative fan speeds) achieved the best results in terms of acceptable IAQ with indoor CO_2 concentrations below the limit set by ASHRAE 62.2 of 700 ppm above the outdoor concentration and the demand-controlled ERV spent a bigger fraction of time on low fan speed (relative fan speed of 20%). The results also suggested that a threshold for difference in CO_2 concentration between supply and exhaust air of 150 or 200 ppm is suitable to ensure switches to higher ventilation rate shortly after a change in occupancy, achieve a good control of the indoor CO_2 concentration, and present higher potential for reducing the electricity consumption by the ERV unit (higher fraction of time on low fan speed).

INTRODUCTION

The energy efficiency of residential buildings has significantly increased since the 1970's and a major component of this improvement has come as a result of reduced uncontrolled air leakage through the building envelope (Wray et al., 2000). Over the same period, changes in building materials, appliances, home furnishings and manufactured products have resulted in new types of indoor pollutants and increased emissions levels (Sherman and Walker 2007). As a result, operable windows and air leakage can no longer be relied upon to provide adequate residential ventilation, particularly in cold climates during winter. In order to provide a healthy indoor environment for building occupants, most

Boualem Ouazia is a research officer, **Chantal Arsenault, Gang Nong and Mark Vuotari** are technical officer in the Construction Research Centre, National Research Council Canada, Ottawa, Ontario, Canada. **Daniel Sanders** was a under-graduate student at Carlton University, Ottawa, Ontario, Canada.

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" (ANSI/ASHRAE Standard 62.2 2017 and CAN-CSA F326 2015). As interest in energy saving grows, balanced supply and exhaust systems are becoming increasingly popular in cold climates because they allow for waste heat to be recaptured from exhausted warm stale air. Without ventilation heat/energy recovery, energy savings from improvements in the airtightness of the building envelope are offset by heat losses due to increased mechanical ventilation. Balanced 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 (Russel et al. 2005). ASHRAE Standard 62.2 and National Building Code (NBC) set the required (constant) ventilation rate, calculated on the basis of fixed liveable floor area and fixed number of bedroom or people. The HRV/ERV units are selected to meet the required ventilation and their selection is based on the calculated minimum ventilation rate.

Balanced ventilation systems (HRVs and ERVs) on the market and installed in northern and remote communities offer constant airflows. Constant ventilation rate is not adequate for varying and high occupancy situations (common in northern communities) leading to poor indoor air quality. Northern and remote communities can also experience periods where houses are unoccupied for long periods of time (hunting and fishing seasons), which leads to unnecessary energy usage. The ventilation rate could be too low for housing experiencing variable indoor conditions such as varying occupancy (overcrowding) encountered in northern homes. Indoor activities could be also higher (RH, pollutants, etc.) producing higher indoor moisture that needs to be controlled to avoid mold problem and deterioration of the building.

The key of an enhanced heat/energy recovery ventilation concept is to use controls (sensors) to ventilate homes to indoor needs. Every ventilation system should strive toward a heat/energy recovery ventilation to save energy, balanced supply and exhaust airflows to prevent pressurization or depressurization, and to provide an adequate ventilation rate for unoccupied homes to save energy and for homes experiencing varying occupancy and indoor activities, to maintain a comfortable and healthy indoor environment. Historically, humidity and CO_2 have been used as indictors of IAQ and therefore used to control DCV systems. CO_2 is often used in DCV strategies, not to prevent negative health effects directly attributed to it, but because it can be representative of other parameters such as concentrations of bio-effluents occupancy rates or ventilation rates.

As part of the project called "Smart Ventilation Advanced for Californian Homes" (Guyot et al., 2018) an exhaustive literature review on smart ventilation was conducted: the suitability of various environmental variables for use as inputs in smart ventilation applications, the availability and reliability of the sensors used to measure these variables, a description of relevant control strategies, and overview of the regulations and standard proposing "equivalence methods" in order to promote the use of smart ventilation strategies, the variable systems on the market in different countries, and a summary of ongoing developments in research areas related to ventilation, including IAQ metrics and feedback from on-site implementations were evaluated. They provided a literature review on smart ventilation used in residential buildings from 1979 to 2016, based on energy and indoor air quality performance. Their meta-analysis included 38 studies of various smart ventilation systems with control based on CO_2, humidity, combined CO_2 and total volatile organic compounds (TVOC), occupancy, or outdoor temperature. The reviewed studies show that ventilation energy savings up to 60% can be obtained without compromising IAQ, sometimes even improving it. However, the meta-analysis included some less than favorable results, with 26% energy overconsumption in some cases.

Northern Housing Ventilation Challenges

Canada's northern and remote communities face an acute overcrowding housing crisis which threatens their health and safety. In Nunavik alone, over half of Inuit families live in overcrowded housing. In far too many communities, up to 15 people, including young children, live in small and crumbling three bedroom units. Overcrowding continues to have serious public health repercussions (disease transmission, etc.) throughout the Inuit territories. Tuberculosis, which is rare in southern Canada, occurs among Inuit at a rate over 250 times higher than for non-indigenous Canadians. High levels of respiratory infections among Inuit children, such as chronic lung disease after lower respiratory tract infections, are also linked to crowding and poorly ventilated homes. Excessive mould is an issue in the overcrowded homes in part because ventilation is specified for the footprint of the house and not the occupancy. Implementing a higher constant flow rate system wouldn't be an adequate solution either, given the dynamic occupancy nature of the communities. This exacerbates the need for more dynamic ventilation solutions based on varying indoor needs, such as demand-controlled ventilation strategies/systems.

Estimation of CO_2 Generation Rates

Indoor carbon dioxide concentrations have been used for decades to characterize building ventilation and indoor air quality. Many of these applications require the rate of CO_2 generation from building occupants. However, the CO_2 generation rates used currently are based on calculational methods and data that are several decades old, and which do not account for individual occupant characteristics such as age, sex and body size. Persily et al. (2016) reviewed how CO_2 generation rates have been estimated in the past and discusses how they could be characterized more accurately. The ASHRAE Fundamentals Handbook (2013) and ASTM D6245 (ASTM D6245-07, 2012) describe the current approach to estimating CO_2 generation rates. A new approach (Persily et al., 2016) uses more recent data on body mass and the basal metabolic rate (BMR) of the individual(s) of interest combined with their level of physical activity. The new approach considers CO_2 generation rates for different space types of interest. The average CO_2 generation rates based on space type are 0.240 L/min/person for a residence, 0.216 L/min/person for an adult bedroom, and 0.150 L/min/person for child's bedroom. These CO_2 generation rates are based on the mean body mass for the assumed occupants in the specific age ranges; they do not account for the variation in body mass within these age ranges. Previous average CO_2 generation rates per person range from about 0.180 to 0.360 L/min, primarily based on the assumed occupant ages and activity levels. The new approach to estimating CO_2 generation rates from building occupants is applicable to groups of individuals, as the theory behind the method and the data are based on groups, not single individuals.

CO_2-BASED CONTROL STRATEGY FOR DC ERV

A demand controlled ventilation was implemented on a basic energy recovery ventilator designed with constant air flows. The control was based on the CO_2 concentration difference between outdoor (measured at the air intake to the ERV unit from outdoors) and exhaust air (measured at the return from the room into the exhaust inlet to the ERV) to adjust the ventilation rate by increasing the supply and exhaust flow rates based on sensing difference in CO_2 concentration. Assuming indoor CO_2 concentration equals the outdoor concentration when the space is unoccupied, and with development of a difference in CO_2 concentration between the extracted air from the test bedroom and supplied outdoor air to the test bedroom in situations when from one to four persons are sleeping in the test bedroom. 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 minimum air flow is used for an unoccupied bedroom and it is adjusted (higher air flows active) 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 the less expensive. A threshold for CO_2 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 (Nielson et al., 2010).

The demand-controlled ERV architecture consists of the proposed CO_2 sensor network combining CO_2 sensors and a central computer. Measurement results at the intake and the return to the ERV or in the indoor space are transmitted to the central control computer via wired communication. The CO_2 sensors have a range of 0-2000 ppm. Their output is an analog voltage, which linearly varies with sensed CO_2 level. As a result, the output voltage of this CO_2 sensor precisely indicates the ambient CO_2 level. The output voltage of a CO_2 sensor should respond to time-varying space occupancy (varying indoor CO_2 concentration). To verify the proposed DC method applied to an ERV, we conducted a series of experiments in a test bedroom of the Indoor Air Research Laboratory (IARL), where we simulated varying presence of occupants sleeping in the bedroom using an automated CO_2 dosing system.

METHOD

The CO_2-based demand-controlled energy recovery ventilator was implemented in a test room of the Indoor Air Research Laboratory (IARL) shown in Figure 1 (left) with varying simulated occupancy. The test bedroom is located in the left section of the building and on the second floor facing south.

Experimental setup for the test bedroom

The concentration level of indoor carbon dioxide is a good indicator of the occupancy rate while protecting the personal privacy of dwelling residents. CO_2 sensors are easy and relatively cheap to install compared to other techniques for occupant detection. Figure 1 (right) illustrates the design of the experimental setup for a test bedroom with the installation of a fully dedicated energy recovery ventilator, deployment of an automated CO_2 dosing system in the room and connected to a CO_2 cylinder located outside the test bedroom. A mixing fan was also deployed to effectively mix the dosed CO_2 with the indoor air in the room. Measured parameters and their locations are also shown in Figure 1 (right).

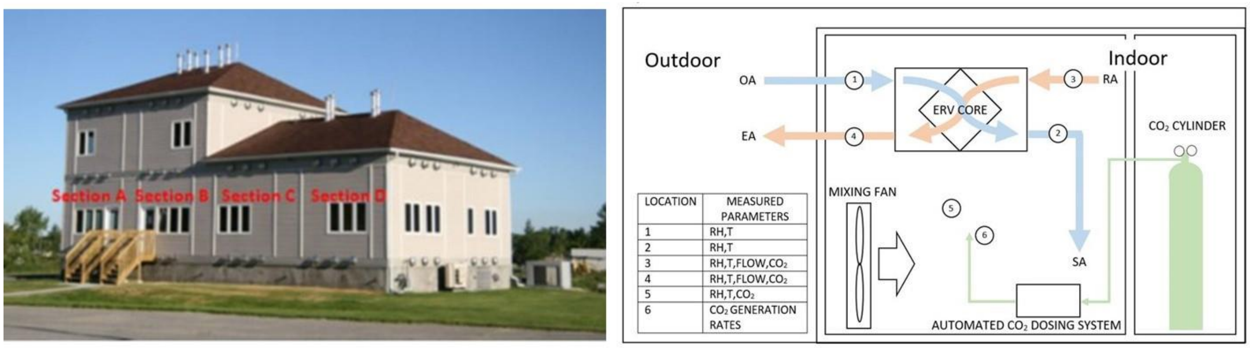

Figure 1. Indoor Air Research Laboratory (left) - Schematic of the test bedroom experimental setup (right).

The ERV unit is an AVS EKO 1.5 ERV which has a design that incorporates high performance ECM motors which consume significantly less electricity, equivalent in power to a compact fluorescent bulb (13.5 watts each), which enable the ERV model to significantly lower energy costs without affecting its performance. Its core absorbs both heat and moisture from the air streams passing through it. In the summer, the heat and humidity of the outdoor fresh air is transferred to the exhaust air stream, meaning the home stays cooler indoors, and the opposite is true in winter.

The ERV unit was connected to the test bedroom with a supply air duct supplying outdoor air at floor level and a return duct exhausting stale air from the room at ceiling level. All existing supply and return registers were sealed (controlled dampers closed) to ensure that ventilation was provided only by the ERV unit. The simulation occupancy was achieved by an automated system installed in the test bedroom and was connected to a CO_2 cylinder installed outside the test bedroom. The indoor conditions in terms of temperature, relative humidity and CO_2 concentration were measured in the centre of the test bedroom. The data acquisition system was also placed outside the test bedroom and consisted of a pressure box with pressure transducers for supply and exhaust airflow measurement, a connection box with connectors for different types of sensors such as RH&T, pressure, CO_2, etc. The instrumented ERV unit was installed outside the test bedroom as a fully dedicated system with outdoor air supplied directly to the test bedroom and stale air drawn directly from the same test bedroom.

Automated CO_2 Doing System

The simulation of different occupancy rates required the design of an automated CO_2 dosing system and a provision of a source of CO_2. The CO_2 gas is delivered from the pure CO_2 cylinder via a pressure regulator. From the cylinder the flow is separated into 4 separate lines. Between the cylinder and each mass flow meter (MFM) is a valve. Each channel has a maximum flow rate which is shown in Table 1. The automated dosing system was designed with a CCR Model 400 4-channels readout and power supply and four MFMs. The Model 400 is a 4-channel stand-alone microprocessor-based configurable digital indicator and power supply capable of interfacing directly to analog mass flow meters, mass flow controllers, or pressure transducers. The instrument configuration and control can be one from the front panel keypad or via the RS-232C or RS-485 interface. The MFC is an all-metal mass flow controller designed to measure and control at the same time the flow of gas via an integrated control valve. It is available in both analog and digital models with accuracies of 1% of Full Scale and 1% of Reading, respectively. The automated CO_2 dosing systems is controlled via the same laptop used for data acquisition.

Table 1. Table Title Is Always in Mixed Case

Channel Number	Maximum CO_2 Flow Rate [L/min]
1	0.76
2	1.52
3	3.78
4	7.70

Instrumentation and Data Acquisition System

Measurements were carried out for a fully dedicated CO_2-controlled energy recovery ventilator for a test bedroom with varying simulated occupancy. Measurements were conducted at the ERV system level and in the indoor test bedroom under steady-state conditions. Measured parameters included (1) temperature at the supply inlet and outlet of the ERV, exhaust inlet and outlet of the ERV and indoors (centre of the test bedroom), (2) relative humidity at the supply inlet and outlet of the ERV, exhaust inlet and outlet of the ERV and indoors (centre of the test bedroom), (3) CO_2 concentration at the supply from the ERV, return from indoor to the ERV and indoors (centre of the test bedroom), (4) supply and exhaust airflows through the ERV and (5) relative fan speed of the ERV supply and exhaust fans. All sensors used to measure the variables listed above were calibrated and their specifications are presented in Table 2.
A Data Acquisition Cart was used to record the sensor values. The cart included a connection box for all deployed sensors (temperature and RH probes, CO_2 sensors) and a pressure box with pressure transducers and power supplies for pressure measurement. The connection box is connected to the Agilent 34980A Data Acquisition Unit connected to the laptop. The automated CO_2 dosing system is connected to the Laptop through USB. The DAQ program controls the CO_2 dosing flow and schedule and also controls the change in the relative fan speed via an Arduino microcontroller to adjust the supply and exhaust air flows based on the selected CO_2 concentration threshold.

Table 2. Specifications of used instrumentation

Type	Model	Calibration Range	Calibration Accuracy
RH & T probe	Vaisala HMP60	-20°C - +40°C 10 to 90%	±0.2°C ±3%
CO_2 probe	Vaisala GMD20	0 – 2000 ppm	±(2% of range + 2% of reading)
Pressure Transducer	Setra	0 – 125 Pa	±1% FS
Air Flow Element	6" Nailor	20 to 200 cfm	±5%
CO_2 Mass Flow Controller/Meter	MKS Series	0 – 0.76, 1.52, 3.78 and 7.70 L/min	±0.8% of set point for 20 to 100% FS

Testing Procedure

The test bedroom simulated occupancy was achieved for up to 4 adults using a CO_2 automated doing system. The CO_2 generation rate by an adult in a bedroom was 0.0036 L/s/person of CO_2. The minimum ventilation rate for the test bedroom when it is not occupied was dictated by the minimum ventilation that could provide the tested ERV which was at a relative fan speed of 20%, equivalent to 30 cfm. We were aware that the minimum ventilation rate of 30 cfm provided by the ERV would be too high for the test bedroom floor area but that it would not affect the quality of the testing. The focus of this testing applied to a bedroom was the proof of concept of a CO_2-based demand controlled energy recovery ventilation and identify the optimum control strategy that would ensure the best control of the indoor CO_2 concentration for acceptable IAQ and the fraction of time the ERV was on low fan speed for energy consumption.

Experiments were performed with a control strategy based on the difference in CO_2 concentration between the return air to the ERV and the supply air from the ERV with three thresholds for difference in CO_2 concentration of 100, 150 and 200 ppm, and the ventilation strategy was to switch the air flow between four levels (relative fan speed of 20%, 50%, 65% and 85%). A 24 hour variable simulated occupancy was performed for up to four adults in the test bedroom starting at noon to noon on the following day. The variable simulation occupancy over 24 hours is presented in Table 3 for Tests 1 to 3 done with occupancy varying every 6 hours (up to 3 adults sleeping in the bedroom) and for tests 4 to 6 done with occupancy varying every 4 hours (up to 4 adults sleeping in the bedroom). The presence of an adult sleeping in the test bedroom was simulated by a CO_2 dosing flow of 0.216 L/min.

Table 3. Variable simulated occupancy over 24 hours

Occupancy [# of adult]	CO_2 Flow Rate [L/min]	Dosing periods	
		Tests 1, 2 & 3	Tests 4, 5 & 6
1	0.216	Noon to 6 PM	Noon to 4 PM
2	0.432	6 PM to 12 AM	4 PM to 8 PM
3	0.648	12 AM to 6 AM	8 PM to 12 AM
4	0.864	-	12 AM to 6 AM
2	0.432	-	6 AM to 10 AM
0	0.000	6 AM to Noon	10 AM to Noon

RESULTS AND DISCUSSION

The test bedroom was ventilated via a fully dedicated CO_2-based demand-controlled ERV system. The ERV supply and exhaust flow rates were controlled by the speed of the supply and exhaust fans and for the low flow rate the fan speeds were at a relative fan speed of 20% of the maximum speeds at the highest supply and exhaust flow rates. The system was tested for varying occupancy in the test bedroom (up to 4 adults) and for three threshold values of difference in CO_2-concentration.

Table 4 shows the measured period of each experimental test, the threshold for difference in CO_2 concentration between exhaust and supply air, and the fraction of time the fans were on the four levels of fan speed. The best results were obtained with a 200 ppm limit on difference in CO_2 concentration. With this threshold of 200 ppm, the ventilation was running with the low ventilation rate (low relative fan speed of 20%) 83% of the time for the experimental test done with a maximum of 3 adults sleeping in the bedroom and 30% of the time for testing done with a maximum occupancy of 4 adults.

Table 4. Experimental Tests

Test #	Measured Period	Threshold [ppm]	Fraction of time on fan speed			
			1	2	3	4
1	06/08 – 09/08 2019	100	69%	19%	12%	0%
2	02/08 – 06/08 2019	150	79%	21%	0%	0%
3	09/08 – 12/08 2019	200	83%	17%	0%	0%
4	03/10 – 08/10 2019	100	14%	45%	41%	0%
5	08/10 – 11/10 2019	150	21%	64%	15%	0%
6	11/10 – 15/10 2109	200	30%	70%	0%	0%

Results are presented for two experimental tests done with maximum simulated occupancy of four adults sleeping in the bedroom, Test 4 and Test 6. Figure 2 shows the plots of the difference in CO_2 concentration between extracted air and outdoor air and relative fan speed over a testing period of 24 hours. These plots show the varying simulated occupancy starting with empty space (no dosing) then increased every 4 hours by one more adult sleeping in the bedroom (by 0.216 L/min for each additional adult in the test bedroom) up to a maximum of four adults, and then down to two adults before stopping the CO_2 dosing for the last two hours of the test on the following day. The high relative fan speed is active when the threshold value of difference in CO_2 concentration is exceeded. With a threshold of 100 ppm the ERV unit went to higher relative fan speed (65%) than with threshold of 200 ppm (relative fan speed at 50%) for occupancy rate of three and four adults sleeping in the bedroom.

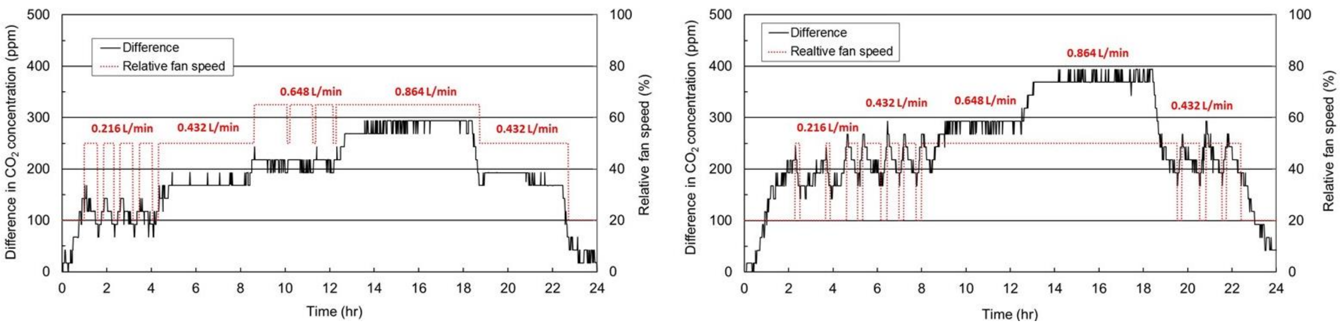

Figure 2. Difference in CO_2 concentration and relative fan speed for Test 4 (left) and Test 6 (right).

Figure 3 shows the plots of the supply and exhaust air flows and relative fan speed for the same tests and over a testing period of 24 hours. These plots show that for the same varying simulated occupancy, the high ventilation rate is active when the threshold value is exceeded. The high relative fan speed is active when the threshold value of difference in CO_2 concentration is exceeded. The highest ventilation rate reached with implemented control based on a threshold of 100 ppm was 95±5 cfm higher than with implemented threshold of 200 ppm of 75±5 cfm for occupancy rate of three and four adults sleeping in the bedroom. It is seen also that the flow rate of the demand-controlled ERV is reduced to the minimum ventilation rate (in this case 30±5 cfm) when the bedroom is not occupied. Longer time spent on low fan speed (reduced ventilation rate) will give significant savings on electrical energy used for ventilation.

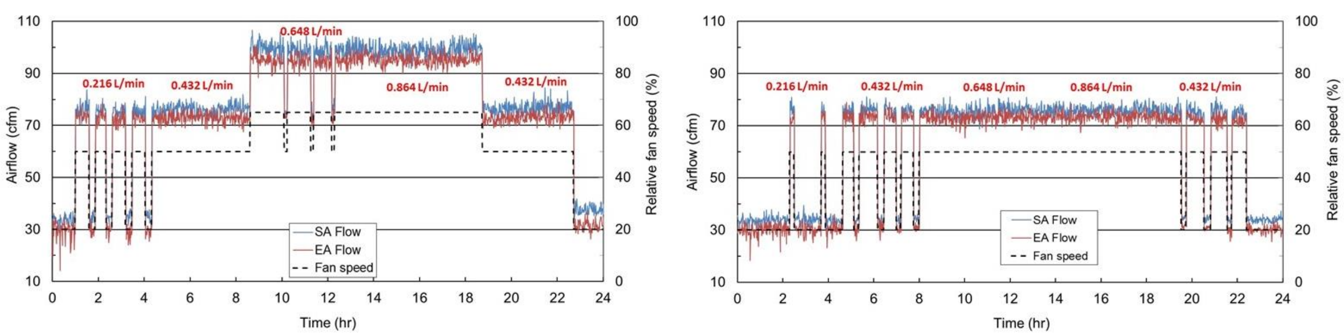

Figure 3. Supply and exhaust air flows and relative fans speed for Test 4 (left) and Test 6 (right).

Figure 4 shows the plots of the CO_2 concentration measured indoors and in supply and exhaust air from the ERV unit over a testing period of 24 hours. These plots show with the same varying simulated occupancy, that a smaller implemented threshold of the difference in CO_2 concentration between extracted air and outdoor air of 100 ppm will achieve a better control of the indoor CO_2 concentration, which was below 1000 ppm at the highest occupancy rate of four adults. With implemented control based on a threshold of difference in CO_2 concentration of 200 ppm, the indoor CO_2 concentration exceeded 100 ppm at the highest occupancy rate of four adults but did not exceed the limit set by ASHRAE 62.2 of 700 ppm above the outdoor CO_2 concentration. Demand control implemented with the low threshold value will reduce the fraction of time the ERV unit is on low fan speed and will increase the electricity consumption for ventilation. The overall results showed that a threshold for CO_2 concentration of 200 ppm is suitable to ensure the ERV system switches to higher ventilation rate shortly after an adult enters sleeping in the bedroom, spend a larger fraction of time on low fan speed, and without exceeding the limit of indoor CO_2 concentration set by ASHRAE 62.2.

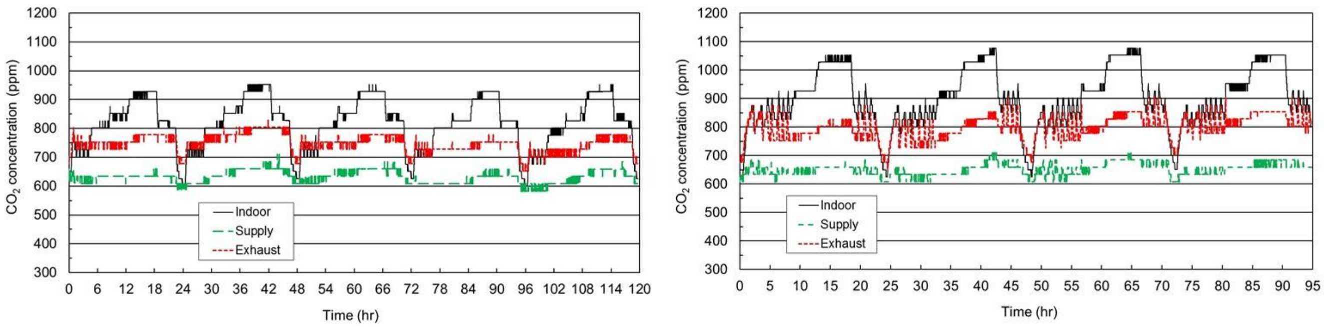

Figure 4. Measured CO_2 concentration measured indoor, supply and return for Test 4 (left) and Test 6 (right).

CONCLUSION

A simple strategy for demand-controlled ventilation was implemented in a test bedroom with varying occupancy extended to a maximum of four adults sleeping in the bedroom. The strategy is based on sensing the difference in CO_2-concentration between extracted air and outdoor air. The implemented control strategy based on switching the ventilation rate between four levels (four relative fan speeds) achieved an acceptable IAQ with indoor CO_2 concentration kept below the limit of 700 ppm above the outdoor CO_2 concentration set by ASHRAE 62.2 with reduced flow rate of the ventilation system during the time where the bedroom is unoccupied. The results suggested that a threshold for difference in CO_2 concentration of 200 ppm is suitable to ensure a good control of the indoor CO_2 concentration and present higher potential for reducing the electricity consumption by the ERV unit (longer fraction of time spent on low fan speed). Demand-controlled ventilation could be a solution to improve IAQ in northern housing experiencing varying occupancy and overcrowding, and at same time could reduce the energy consumption for periods where the house is not occupied. Future work will focus on the performance of a CO_2-based demand-controlled residential ventilation system for a typical residential apartment with zonal and varying simulated occupancies.

ACKNOWLEDGMENTS

This research project was funded by the Government of Canada's "Action on Air Pollution" and NRC's Climate Change and Air Pollution programs. We would like to thank Venmar Ventilation Inc. for the ERV unit and Loic Ares for his technical support.

REFERENCES

ASHRAE. 2005. *ASHRAE Handbook—Fundamentals*. Atlanta: ASHRAE.

ANSI/ASHRAE Standard 62.2 "Ventilation and acceptable indoor air quality in low-rise residential buildings" 2013:2016.

ASTM (D6245-07) "Standard Guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation" 2012.

CSA F-326 (2013). National Standard of Canada CAN/CSA-F326-M91 "Residential Mechanical Ventilation Systems" Canadian standard Association, Toronto, Canada.

G. Guyot, M.H. Sherman, I.S. Walker "Smart ventilation energy and indoor air quality performance in residential buildings: A review" Energy & Buildings 165 p. 416-430, 2018.

National Building Code of Canada (NBCC) 2015.

T.R. Nielsen, C. Drivsholm "Energy efficient demand controlled ventilation in single family houses," Energy Build 42, pp. 1995-1998, 2010.

A. Persily, L. de Jonge "Carbon dioxide generation rates for building occupants" Indoor Air, 27 p. 868-879, 2017.

M. Sherman, I. Walker, I. "Air Distribution Effectiveness for Different Mechanical Ventilation Systems" Lawrence Berkeley National Laboratory, LBNL-62700. 2007.

C.P. Wray, N.E. Matson, and M.H. Sherman "Selecting Whole-House Ventilation Strategies to Meet Proposed Standard 62.2: Energy Cost Considerations". ASHRAE Transactions, 106: 681, 2000.