# Performance of a Heat Recovery Ventilation System in the Canadian Arctic

Justin Berquist*[1], Carsen Banister[1], and Dennis Krys[1]

*1 National Research Council Canada*

*1200 Montreal Road, Ottawa, Ontario, K1A 0R6*

*Canada*

**Corresponding author:*
*justin.berquist@nrc-cnrc.gc.ca*

## ABSTRACT

A demonstration house was previously built and commissioned in Iqaluit, Nunavut, Canada. The purpose of the overall effort is to evaluate the performance of a high-performance building located in the Canadian Arctic, while considering the unique social, economic and logistical challenges associated with its remote location. Previous work consisted of monitoring and reporting on the energy consumption due to heating between April 2016 and April 2017. The purpose of this ongoing research is to contribute experimental data regarding the functionality of ventilation systems in cold climates. This paper outlines the development, implementation and monitoring of a carbon dioxide-based demand-controlled heat recovery ventilation system that took place between April 2017 and April 2019. The system was equipped with two electric preheaters to ensure that frost build-up did not occur in the heat recovery ventilator (HRV) and adequate fresh air ventilation could be maintained. An electric heater was included after the HRV to control the supply air temperature. Monitoring of the ventilation system's performance took place between December 2018 and February 2019. During this period the electricity consumption of the HRV, preheaters, and supply air heater were measured for the fresh air required for two "theoretical" occupants. Flow rate and important temperatures in the ventilation system were also monitored to assess the system's performance. A comparison of the sensible recovery efficiency (SRE) of the HRV and overall system is presented. Experiments displayed that on average the SRE of the system and HRV was 35% and 72%, respectively. The total energy consumption of the ventilation system was 390 kWh over the two months, which translates to 6.30 kWh/day, an energy use intensity of 0.27 kWh/m$^2$/day and 4.49 Wh per L/s of fresh air.

**Keywords:** heat recovery ventilator, ventilation, demand control, energy performance, and cold climate.

# 1 INTRODUCTION

There are multiple challenges associated with housing in northern Canada. Firstly, the cost of supplies and labour are increased in remote locations (Roszler, 2005) and the cost of heating is substantially higher due to the cold climate (Minich, et al., 2011). Furthermore, extremely cold climates result in durability issues with houses and their systems, which can result in health problems (Minich, et al., 2011). An Inuit Health Survey was conducted to evaluate the living conditions in a total of 1,901 households. From the survey it was concluded that approximately 40% of the homes were in need of major repairs, 30% were overcrowded and 20% contained mould (Minich, et al., 2011).

The occurrence of mould growth in these homes suggests a need for better building envelopes and proper ventilation. The research outlined by Banister et al. (2018) presented a better building envelope solution in cold climates. However, a limited amount of research has been directed at solving ventilation issues in cold climates. The large difference between outdoor and indoor temperatures during much of the year in these locations makes it highly valuable to control ventilation rates effectively and have a system that manages ventilation air heating energy well. Equipment for air to air heat/energy recovery is an effective method of reducing the cost associated with ventilating the home (Nasr, Kassai, Ge, & Simonson, 2015). Heat recovery ventilators (HRVs) were utilized by Kovesi et al. (2009) and successfully allowed for a reduction of indoor air pollutants and in the number of reported respiratory infection symptoms in Inuit children. However, the extreme temperature difference between the fresh air and indoor temperature can cause problems, such as frosting, in the mechanical equipment, which can cause the performance of equipment to degrade (Nasr, Kassai, Ge, & Simonson, 2015), or system failure (Kragh, Rose, & Svendsen, 2005).

While these challenges are difficult to overcome, they need to be addressed for the living standards and occupant health to be increased in northern communities (Minich, et al., 2011). Therefore, this paper aimed to address this gap in research through the development and implementation of a ventilation system within the Iqaluit demonstration house which combines effective use of low-cost $CO_2$ sensors for demand-controlled ventilation, ventilation system modifications to enable more fan speeds, preheaters to reduce the need for defrost cycles when desired, and a supply air heater to achieve satisfactory thermal comfort. Moreover, this paper provides experimental data regarding the operation of a ventilation system in a cold climate, an area that is limited in literature.

# 2 LITERATURE REVIEW

Due to the high energy costs in the Arctic it is very beneficial to ventilate on an “as needed” basis. For this reason, literature related to residential demand control ventilation (DCV) strategies was reviewed. Furthermore, literature pertaining to ventilation systems in cold climates was also reviewed due to the difficulties associated with ventilating in extreme cold.

## 2.1 Residential Demand Control Ventilation Strategies

Kim & Park (2009) studied eight ventilation strategies in a 5-story apartment building in Jeju, Korea. The eight strategies consisted of either constant air volume (CAV) or $CO_2$-based DCV systems, and varying locations of the supply and $CO_2$ sensors. CONTAMW 2.4 simulations revealed that the CAV systems are more advantageous in terms of initial cost, when compared to the $CO_2$-based DCV systems. They were also most advantageous in terms of percent dissatisfied and $CO_2$ concentration because of the constant supply of sufficient outdoor air. However, the $CO_2$-based DCV methods have a lower energy cost, and the investment payback periods are short.

Cho, Song, Hwang & Yun (2015) evaluated the energy saving potential of a demand-control ventilation system with an air-cleaning unit in a multi-residential building. The ventilation system operates based on the indoor $CO_2$ and HCHO concentrations. The ventilation and air-cleaning modes operate independently or simultaneously to optimize the energy usage for ventilation. Results obtained through TRNSYS displayed that the proposed ventilation system, when compared to continuous ventilation methods, decreases the introduction of fresh air approximately 50% of the operating time and the energy use by approximately 20%.

Cleveland & Schuh (2010) designed an automated thermostat that operates based on the occupancy of the ecoMOD1 house. The occupancy of the house was determined by utilizing a combination of carbon dioxide sensors and motion detectors on each floor. When an occupant was detected in the house the thermostat would adjust the set-point temperature accordingly. It was determined that a concentration level of 525 ppm was necessary to denote the house as occupied. However, the time needed to reach this level can range up to twenty minutes, therefore the system also considered the rate of change of the carbon dioxide.

Guyot, Sherman & Walker (2018) reviewed 38 studies related to smart ventilation systems, which operate based on $CO_2$, humidity, combined $CO_2$ and total volatile organic compounds (TVOC), occupancy and outdoor temperature. The literature review displayed that ventilation energy savings of up to 60% can be achieved without jeopardizing the IAQ of the space. However, the meta-analysis revealed studies that resulted in a 26% increase in energy consumption. The literature review presents a well-documented table outlining the type of home, utilized controls strategy, the main findings, and the resulting IAQ performance and energy savings of each reviewed research study.

## 2.2 Ventilation Systems in Cold Climates

Liu, Alonso, Mathisen & Simonson (2016) built and tested a novel quasi-counter-flow membrane energy exchanger during cold operating conditions. A moisture transfer diffusive resistance of dense and porous membrane was derived for cold climates. The sensible and latent effectiveness was found to vary between 88.5% to 94.5% and 73.7% to 83.5%, respectively.

Nielsen, Rose & Kragh (2009) developed a dynamic model of a counter flow air to air heat exchanger in Simulink. The model took into account condensation, frosting and melting, in order to accurately simulate its performance in cold climates. It is shown through experimentation and simulation that ice will begin to form in a heat exchanger, unless defrosting methodologies are deployed.

Nasr, Kassai, Ge & Simonson (2015) experimentally tested two cross-flow heat/energy exchangers during frosting and defrosting cycles. The effect of two defrosting methods (preheating and bypassing), on energy consumption of ventilation in three locations was evaluated. It was determined that preheating the fresh air performs better than the heat exchanger bypass method. Also, it was found that cold weather conditions impact heat recovery ventilators more than energy recovery ventilators.

Further, more in depth reviews of heat and energy recovery ventilators, and frosting in cold climates were completed by Nasr, Fauchoux, Besant & Simonson (2014) and Alonso et al. (2015). Nasr et al. (2014) provided a detailed review regarding frosting in heat and energy recovery ventilators. Alonso et al. (2015) summarized literature pertaining to key technologies that are ideal for zero energy buildings located in cold climates.

## 2.3 Summary of Literature Findings

The review on literature pertaining to DCV revealed that careful consideration to the control strategy is required to obtain positive indoor air quality and energy savings. Due to low occupant densities $CO_2$ may be a poor indicator of occupancy in residential applications. However, it is believed that the over-crowding associated with northern housing makes this a viable option. The review on literature regarding ventilation systems in cold climates revealed that defrosting methods are necessary for heat and energy recovery ventilators to maintain functionality in cold climates (Zeng, Liu, & Shukla, 2017). The literature revealed that the cost of novel defrosting methods can be high, the equipment can be bulky and there is limited experimental data (Zeng, Liu, & Shukla, 2017) and that other defrosting techniques cut off the supply of fresh air for an extended period of time, defeating the purpose of a ventilation system. As a result, preheating was considered an effective method for preventing frosting in this research due to its low initial cost, non-invasiveness and the added benefit of a continuous supply of fresh air.

# 3 METHODS AND MATERIALS

This section describes the design of the ventilation system, the ventilation system controls strategy for the DCV system and preheaters, and the sensors utilized to monitor the performance of several aspects of the ventilation system.

## 3.1 Ventilation System Design

The system was designed with two 1 kW preheaters to make use of an off-the-shelf HRV and avoid inadequate ventilation from occurring. To avoid or remove frost build up, the HRV has a factory-set defrost strategy which switches the unit into recirculation mode on an increasing proportion of time as the HRV inlet temperature decreases below -5 °C. The supply air temperature that exits the HRV will vary based on the indoor temperature set point and the outdoor temperature. Furthermore, the supply air temperature could also be low relative to the indoor temperature, resulting in cold drafts within the spaces, as was found to be the case in (Kragh, Rose, & Svendsen, 2005). To ensure a comfortable supply air temperature would be reached prior to entering the space, a 1 kW electric heater was included on the supply air stream to control the delivered temperature. The fresh air and exhaust ducts were insulated with R4 reflective insulation to reduce heat gains from the space.

## 3.2 Ventilation System Controls

Having established the equipment required to achieve desired indoor conditions through ideal ventilation rates, a control strategy was developed for the DCV system and the preheaters.

### Demand Control Ventilation Strategy

New HRV fan speeds were enabled to allow the $CO_2$-based DCV system to meet a wider range of occupant densities, without excessive over-ventilation. The HRV was modified by replacing the standard transformer with an alternative supplied by the manufacturer. A relay control board was also integrated to allow the system to switch between the speeds of the new transformer. An Arduino microcontroller was used to control the system based on $CO_2$ concentration measurements in the main room of the building. The Arduino collects the data from a $CO_2$ sensor and controls the speed of the fan in the HRV according to the predefined carbon dioxide concentration thresholds. Table 1 shows the operational modes of the HRV, the corresponding airflow rate, and the $CO_2$ concentrations that trigger each flow rate when the $CO_2$ concentration is rising and falling.

Table 1: HRV control modes and corresponding airflow rates

| **HRV mode** | **Airflow rate (L/s)** | **$CO_2$ concentration thresholds (ppm)** | |
|---|---|---|---|
| | | **When rising** | **When falling** |
| Fan speed 1 | 13.5 | - | 700 |
| Fan speed 2 | 21.0 | 700 | 1000 |
| Fan speed 3 | 40.5 | 1300 | - |

### Preheater Control Strategy

The analysis of measurements from an existing ventilation system with heat recovery used in single-family houses in Denmark and a test of a standard heat recovery unit in the laboratory have clearly shown that problems occur when the outdoor temperature gets below approximately –5 °C (Kragh, Rose, & Svendsen, 2005). For this reason, and to avoid the built in defrost mode of the HRV the preheater strategy was set to a static minimum temperature of -5 °C. Although the moisture content of the return air could be considered an input to the preheater temperature control, it was determined at this time that the added complexity and reliance on a humidity sensor, which could fail, was not warranted.

## 3.3 Monitoring of System Performance

The system was equipped with several sensors to allow for the performance of several components to be monitored. This section outlines the various parameters and corresponding sensors that were utilized to monitor the performance of the $CO_2$-based DCV strategy and the performance of the HRV, preheaters and supply air heater.

### $CO_2$-based DCV control strategy performance

The performance of the $CO_2$-based DCV system was monitored On November 26th and 27th, 2018. These two dates were selected for performance monitoring as the demonstration house was unoccupied for an extended period of time, starting November 28th. Occupancy was recorded manually and the operation of the DCV system was monitored through the utilization of two $CO_2$ sensors located in the space and an airflow sensor in the fresh air duct. The HRV mode and airflow measurement can then be analyzed to verify if the system was operating as expected.

### HRV performance

The current and voltage that is supplied to the HRV is measured by a WattsOn power meter, allowing for the power and energy consumption of the HRV to be recorded. In addition to the power and energy consumption information, six thermocouples located on the HRV's core are utilized to measure the HRV's performance. The intake and return air streams are assumed to be well mixed, and thus one thermocouple for each stream was utilized. During the heat exchange a temperature distribution arises for each air stream. For this reason, thermocouples were placed on the bottom, center and top of the core's exhaust side. This allowed for a quadratic temperature distribution to be fit to the exhaust air stream, leading to the determination of the average exhaust temperature. The core's supply side temperature distribution was assumed to be the same as the exhaust side, allowing for an approximation of the average supply air stream temperature.

The performance of the HRV was monitored by evaluating its sensible recovery efficiency (SRE). Equation 1 represents the equation utilized to calculate the SRE of the HRV and accounts for the energy added to the supply air stream via electrical consumption, HRV case heat gains, cross flow leakage and the energy used to defrost.

$$SRE_{HRV} = \frac{\dot{m}\times c_p\times(T_s - T_I) - \dot{Q}_{\mathrm{sf}} - \dot{Q}_{\mathrm{C}} - \dot{Q}_{\mathrm{L}} - \dot{Q}_{\mathrm{D}}}{\dot{m}\times c_p\times(T_R - T_I) + \dot{Q}_{\mathrm{ef}}} \tag{1}$$

where

$SRE_{HRV}$ = sensible recovery efficiency of heat recovery ventilator
$\dot{m}$ = mass flow rate of air (kg/s)
$c_p$ = specific heat capacity of air (J/kgK)
$T_s$ = supply temperature (K)
$T_I$ = inlet temperature (K)
$T_R$ = return temperature (K)
$\dot{Q}_{\mathrm{sf}}$ = energy added to the supply stream by the supply fan (W)
$\dot{Q}_{\mathrm{ef}}$ = energy added to the exhaust stream by the exhaust fan (W)
$\dot{Q}_{\mathrm{C}}$ = energy added to the supply stream due to heat transfer through casing (W)
$\dot{Q}_{\mathrm{L}}$ = energy added to the supply stream due to cross flow leakage (W)
$\dot{Q}_{\mathrm{D}}$ = energy transferred to the HRV core during defrost, from the space (W)

The HRV power data is utilized to determine when the HRV is operating in defrost mode. The HRV operates at the maximum fan speed when it is in defrost mode, and thus will consume the most electricity at this time. For this reason, it is assumed that the HRV is in defrost mode when it is consuming over 50 W.

## Preheater and supply air performance

The current and voltage that is supplied to the three electric heaters (two preheaters and one supply air heater) is measured by a WattsOn power meter, allowing for the power and energy consumption of the HRV to be recorded. In addition to the power and energy consumption information, the outdoor temperature and temperature after the electric preheaters is measured, allowing for the functionality of the preheater control strategy to be monitored.

## System Performance

The performance of the system is monitored by evaluating its SRE. Equation 2 represents the equation utilized to calculate the SRE of the system and is the energy required to raise the fresh air temperature from the outdoor temperature to the supply temperature, adjusting for the energy added to the system via electrical consumption, duct heat loss/gain, HRV case heat loss/gain, cross flow leakage and the energy used to defrost.

$$SRE_{Sys} = \frac{\dot{m}\times c_p\times(T_s - T_O) - \dot{Q}_{\mathrm{ph}} - \dot{Q}_{\mathrm{sf}} - \dot{Q}_{\mathrm{sd}} - \dot{Q}_{\mathrm{C}} - \dot{Q}_{\mathrm{L}} - \dot{Q}_{\mathrm{D}} - \dot{Q}_{\mathrm{sh}}}{\dot{m}\times c_p\times(T_{Room} - T_O) + \dot{Q}_{\mathrm{ef}} + \dot{Q}_{\mathrm{ed}}} \tag{3}$$

where

$SRE_{Sys}$ = sensible recovery efficiency of system
$\dot{m}$ = mass flow rate of air (kg/s)
$c_p$ = specific heat capacity of air (J/kgK)
$T_s$ = supply temperature (K)
$T_O$ = outdoor temperature (K)
$T_{Room}$ = room temperature (K)
$\dot{Q}_{\mathrm{sf}}$ = energy added to the supply stream by the supply fan (W)
$\dot{Q}_{\mathrm{ef}}$ = energy added to the exhaust stream by the exhaust fan (W)

$\dot{Q}_{ph}$ = energy added to the supply stream by the preheater (W)
$\dot{Q}_{sh}$ = energy added to the supply stream by the post HRV heater (W)
$\dot{Q}_{sd}$ = energy added to the supply stream due to heat transfer/leakage from the duct (W)
$\dot{Q}_{ed}$ = energy added to the exhaust stream due to heat transfer/leakage from the duct (W)
$\dot{Q}_{C}$ = energy added to the supply stream due to heat transfer through casing (W)
$\dot{Q}_{L}$ = energy added to the supply stream due to cross flow leakage (W)
$\dot{Q}_{D}$ = energy transferred to the HRV core during defrost, from the space (W)

# 4 RESULTS

The functionality of the $CO_2$-based DCV system was verified on November 26th and 27th, 2018, Afterward, the performance of the HRV, preheaters and supply air heater were monitored for two months, starting on December 1st, 2018 and ending on February 1st, 2019.

## 4.1 $CO_2$-based DCV system performance monitoring

A two-day experiment was conducted on November 26th and 27th, 2018 to verify the functionality of the $CO_2$-based DCV system. The occupancy was varied from no occupancy to up to five occupants during these two days. Figure 1 shows the measured $CO_2$ concentration, fresh air supply rate and number of occupants present in the space.

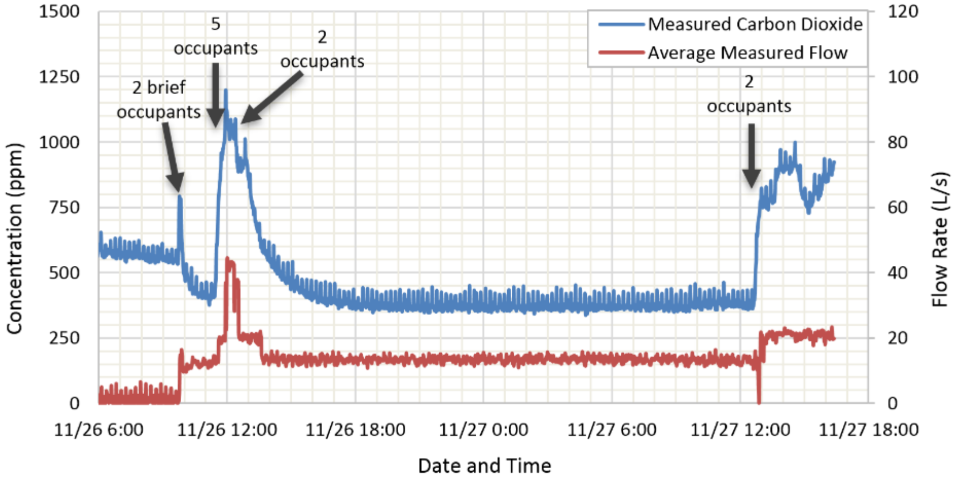

Figure 1: Sample data of demand-controlled ventilation system operation

Initially, the measured $CO_2$ concentration was above outdoor ambient as a result of previous occupancy and no fresh air supply. Two occupants briefly entered the space to enable the system. Their presence caused the $CO_2$ levels to increase, and enabling the system caused the HRV to enter fan speed 1 (13.5 L/s of fresh air). The occupants leaving, combined with the increase in fresh air supply caused the $CO_2$ concentration to decrease back to outdoor ambient. When five occupants entered the space, the $CO_2$ levels increased, causing the HRV to enter fan speed 2 (21 L/s of fresh air), followed by fan speed 3 (40.5 L/s of fresh air). The $CO_2$ concentration stabilized at approximately 1050 ppm until three occupants left. The three occupants leaving caused fan speed 3 to decrease the concentration in the space to below 1000 ppm, causing the fan to switch to speed 2. After the two occupants left, the $CO_2$ levels decreased below 700 ppm, which caused the fan to switch to speed 1. Eventually ambient $CO_2$ concentrations were reached in the space once again. The next day two occupants entered the space, causing the $CO_2$ concentration to increase above 700 ppm. This caused the HRV to enter speed 2, stabilizing the $CO_2$ levels below 1000 ppm.

## 4.2 System energy and SRE performance

The energy performance and SRE of the system was monitored between December 1st, 2018 and February 1st, 2019.

## Energy performance monitoring

While monitoring the system the average outdoor temperature was -26.9 °C and the daily energy consumption of the HRV, preheaters, supply air heater and total system was 0.55 kWh, 3.19 kWh, 2.56 kWh and 6.30 kWh, respectively. Although two months of monitoring data is available, one week will be presented for clarity purposes. Figure 2 shows the energy consumption of the preheaters, supply air heater and the HRV, as well as the HRV inlet and outdoor temperature during the first week of December. The energy data provided in **Error! Reference source not found.** consists of a 10-minute moving average of 1-minute data.

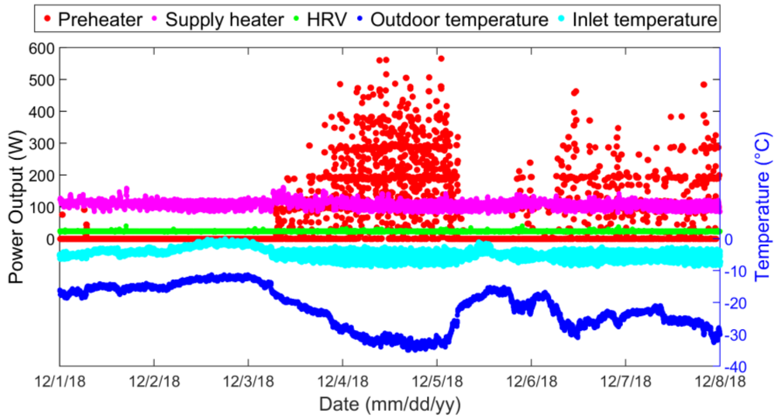

Figure 2: Energy consumption of system from December 1st to December 8th, 2018

Figure 2 shows that the supply air heater constantly provided heat to maintain a supply air temperature of 18 °C. Since the building was unoccupied during this time, the DCV system mainly operated in fan speed 1, the lowest available fresh air supply rate. The HRV operated in defrost mode a few times in January, even though preheat was available. Figure 2 shows that the preheater control strategy was functional, however, minimal preheat was utilized during the week. Figure 2 shows that as a result of an increase in outdoor air temperature, the preheaters stopped supplying heat to the fresh air. The increase in outdoor air temperature did not exceed -10 °C. However, the fresh air was warmed up in the duct before the HRV, by the space. This was a result of the low 13.5 L/s flow rates and 3 m length of fresh air duct, which was found to heat fresh air by as much as 12 °C, without the utilization of preheat.

## Sensible recovery efficiency (SRE) monitoring

While monitoring the system the average outdoor temperature was -26.9 °C, the average SRE of the HRV was 72%, the average SRE of the system was 35% and the system delivered fresh air 98% of the time. Although two months of monitoring data is available, one week will be presented for clarity purposes. Figure 3 shows the SRE of the system and HRV, and the HRV inlet and outdoor temperature for the first week of December. The SRE of the system and HRV was not calculated when the HRV was operating in defrost mode (i.e., when there was no fresh air flow) to ensure validity and accuracy of the calculations, instead these times are displayed as 0 in Figure 3.

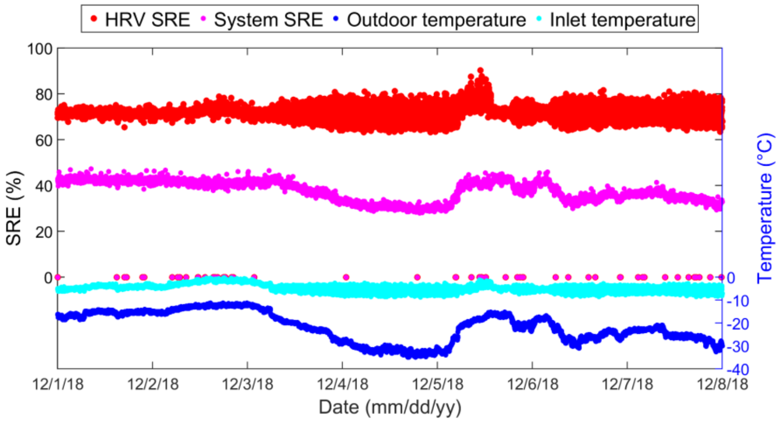

Figure 3: SRE of the system and HRV from December 1st to December 8th, 2018

Figure 3 shows a significant drop in the SRE of the system from the SRE of the HRV. The large discrepancy is a result of the extremely low temperatures causing the preheaters to consume more energy and the fresh air duct to gain excessive energy from the space. The SRE of the system constantly changes, whereas the SRE of the HRV is fairly constant. The SRE of the system is dependent on the outdoor temperature and follows an almost identical trend. As a result of the preheaters, the SRE of the HRV is not dependent on the outdoor temperature. Instead, it is dependent on the inlet temperature. Since the preheaters are unable to maintain a steady inlet temperature for the HRV, the calculated SRE for the HRV is scattered. Although the SRE of the HRV is dependent on the inlet temperature, this dependency is likely exaggerated as a result of the simultaneous measurements in the HRV, when in fact there is a time delay between the supply temperature that results from the inlet and return temperatures.

# 5 DISCUSSION

## 5.1 $CO_2$-based DCV system performance

The two-day testing of the DCV system proved the viability of using low-cost $CO_2$ sensors for ventilation control. Further testing will be conducted in the future to develop a more in-depth analysis of the DCV system's performance. However, the two-day study sufficed for testing the demand-control strategies and showed that if occupants were to enter the space temporarily, sufficient fresh air would be supplied to them.

The detection of occupancy is important for health reasons; accurate occupancy detection allows for appropriate fresh air supply rates to the space. In addition to health reasons, occupancy detection is important for energy conservation purposes. Ventilation systems can be made more efficient by selecting the defrosting method based on the DCV system. For example, recirculating indoor air to defrost the core of the HRV temporarily stops fresh air from being supplied to the space, which is undesirable during high occupancy. However, it utilizes less energy than preheating, and thus at times when no or less fresh air is required during no or low occupancy, recirculation could be utilized instead of preheating. On the other hand, when occupancy is detected, preheat can be used to ensure that continuous fresh air is being supplied to the occupants, albeit, with slightly higher energy consumption.

$CO_2$-based DCV for residential applications has had negative findings as a result of low occupant densities being difficult to detect. However, $CO_2$-based DCV seems more appropriate in the Arctic as housing can become much more overcrowded in the north, negating this reported disadvantage. Moreover, the necessity to supply fresh air on demand is exemplified in Arctic locations given the extreme, cold temperatures.

## 5.2 System energy and SRE performance

The system operated well during the two-month period. The preheaters consistently maintained HRV inlet temperatures around -5 °C, resulting in 3.19 kWh of heating energy used daily. However, the HRV entered defrost 2% of the time, which shows that the preheaters allowed the inlet temperature to drop below -5 °C as the HRV's defrost settings initiate at temperatures below -5 °C. The reason the HRV entered defrost was likely a result of unsteady control of the preheaters, which allowed for the inlet temperature to fluctuate slightly. The energy consumed by the HRV was minimal, at 0.55 kWh per day. To limit drafts of cool air in the building, the supply air was heated to 18 °C after the HRV, resulting in 2.56 kWh of daily heating energy use. The total energy associated with tempering and supplying the building's fresh air was 4.49 Wh per L/s during the two-month testing period.

When the HRV was supplying fresh air to the building it was, on average, recovering sensible energy at a rate of 72%. However, as a result of electrical consumption and duct gains from the space, the SRE of the system was, on average, only 35%. Although insulation was installed on the fresh air duct, the fresh air was able to be heated by as much as 12 °C, without the utilization of preheat, as a result of the low, 13.5 L/s flow rates and 3 m length of R4 insulated duct. This finding indicates an even stronger need for proper installation of exceptional insulation on the fresh air duct, in cold climates. In addition, better insulation should be installed on the exhaust duct to avoid unnecessary system losses, which will be exemplified in extremely cold climates. Moreover, the lengths of the ducts that penetrate through the building envelope should be limited as much as possible.

## 5.3 Comparison of system performance of recirculation vs. preheat

It is often believed that preheating consumes an excessive amount of energy when compared to other defrosting methodologies and is not economical for long cold seasons (Nasr, Kassai, Ge, & Simonson, 2015). However, a theoretical analysis can be conducted to show that the energy consumption of preheating vs. recirculating for frost prevention is relatively comparable.

Consider an outdoor air temperature of -25 °C, fresh air supply rate of 10 L/s, HRV effectiveness of 67%, and a return and supply temperature of 20 °C. Without preheating, the HRV would warm up the outdoor air to 5 °C. To get the air to 20 °C, the supply air heater would have to deliver approximately 150 W of heat to the air. On the other hand, if the air is preheated to -10 °C, the preheater would also consume approximately 150 W. The HRV will then warm up the air to 10 °C, requiring an additional 100 W to be added to the air to get it to the desired 20 °C setpoint. Therefore, without preheat, the system consumes roughly 40% less energy. However, this does not consider the additional costs of defrosting the core via increased fan speeds and heat lost from the space to the core of the HRV during recirculation. Thus, the energy savings of frost prevention via recirculation are slightly lower than calculated.

Although it is recognized that preheat as a frost prevention technique causes the ventilation system to consume more energy than other defrost methodologies, the purpose of the ventilation system is to provide the building and occupants with fresh air. Relying on recirculation as a defrost technique can cause the fresh air supply to be cut off for a high proportion of time, which goes against the purpose of the ventilation system. For periods of high occupancy or humidity, preheating is an important technique to ensure sufficient fresh air can be delivered to a space to maintain acceptable indoor air quality. Preheat also has the added benefit of reducing or avoiding cycles of condensation and/or frost build-up and removal from the core, which could result in less required maintenance.

Another strong reason for using preheating instead of recirculation is that it reduces noise from the ventilation system. For periods of moderate occupancy, it is likely more preferred by occupants for the fan to operate at a medium speed rather than the maximum. If preheat is not used, the HRV fan speed will alternate to a maximum flow rate during recirculation, which can occur every 23 minutes for this particular HRV model. These frequent alternations in fan speed and high levels of noise during recirculation could lead occupants to disable their ventilation system. Additionally, the system will be operating continuously at the highest fan speed at higher occupancy levels, whereas the system utilizing preheat would be able to run continuously at lower fan speeds at the same occupancy levels.

## 6 CONCLUSION

A demonstration house in Iqaluit was equipped with a ventilation system consisting of a heat recovery ventilator, two preheaters and a supply air heater. The system was instrumented with thermocouples, an airflow sensor and current transducers to perform long term monitoring of the system performance. While long term monitoring is ongoing, short term experimental data regarding the functionality of the ventilation system is provided in this paper. The two-day testing of the DCV system proved the viability of using low-cost $CO_2$ sensors for ventilation rate control. While two-months of monitoring the system displayed the systems functionality in the extreme cold. Contrary to some belief that preheating is an undue approach for frost prevention in heat/energy recovery ventilators, this research finds that this method can be acceptable if controlled well. It is important to design building systems as efficient as possible; however, these systems must function and effectively serve their purposes. In the case of a ventilation system, the purpose is to provide fresh air to the building and defrosting reduces the proportion of time when fresh air is delivered, possibly to an unacceptable point to the occupants.

## 7 FUTURE WORK

The development of efficient and comfortable residential buildings in cold climates will continue to be a focus of future work. In the future, measured indoor $CO_2$ concentrations could be used to influence the setpoint of the preheaters. When the building is unoccupied, the preheaters could be disabled, and a lower effective fresh air delivery rate could be accepted, i.e., permit recirculation. When occupants are present, the preheater setpoint would be re-enabled, avoiding the need for defrost cycles. This would restore the effective fresh air delivery rate to the supply air rate, i.e., avoid recirculation. This strategy allows for heat recovery to be maximized and the energy consumption minimized, as the air will only be preheated when the space is occupied, and frosting is possible. Additionally, future experiments will be conducted to build on the theoretical comparison of preheating and recirculating for frost prevention and evaluate the system performance at various fresh air flow rates. The energy consumption of each methodology per unit of fresh air delivered to the space will be utilized to measure the performance of each technique at the respective operational fresh air rate.

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