Intervention field study in the Canadian arctic: Improving ventilation, indoor air quality, and the respiratory health in Nunavik dwellings and children

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Abstract. Homes with inadequate ventilation and indoor air quality (IAQ) are particularly common in northern and remote communities. Previous studies have observed that the indoor air in these homes can have elevated concentrations of CO₂, environmental tobacco smoke, and elevated relative humidity leading to mold issues. These conditions may cause various health problems, such as compromised respiratory health for the occupants and in particular in children with developing respiratory systems. The objectives of this current study were to measure the effectiveness of a targeted optimization of existing heating and ventilation systems at improving ventilation, IAQ, and the respiratory health of children. This study enrolled homes with children under the age 10 in both an intervention group and control group over the winter and spring of 2017-18 in Kuujjuaq, Québec, Canada. Various IAQ, ventilation, and behavioural characteristics were measured both before and after the intervention. Following the intervention, we observed statistically significant reductions in the median values a number relevant IAQ parameters. This study demonstrated that targeted preventative maintenance and optimization of ventilation systems can significantly improve ventilation rates and IAQ.

1. Introduction
Buildings and residences with inadequate ventilation and poor indoor air quality (IAQ) are particularly common in the Canadian arctic [1, 2]. Previous studies have also shown that the indoor air in these homes can have elevated concentrations of carbon dioxide, tobacco smoke, particulate matter, and a low relative humidity [3, 4]. There are also a number of occupant behaviors and characteristics, such as overcrowding, specific to northern communities which can also negatively impact IAQ [5-7]. These conditions may cause various health problems, such as compromised respiratory health and increased incidences of tuberculosis infections, for the occupants and in particular in children with developing respiratory systems [8,9]. There has been limited research on the impact of inadequate ventilation on IAQ and the respiratory health of children. Nunavik public health officials observed an incidence rate of childhood tuberculosis that was over 290 times more elevated amongst Inuit children than Canadian-born non-indigenous children [2]. Prior research has suggested that increased ventilation may be associated with reduced concentrations on indoor air contaminants in the home and may be beneficial to reduce the respiratory symptoms of asthmatic children in artic regions [10]. This in part motivated the present study were we measured the relative effectiveness of different heating and ventilation systems, such as heat and energy recovery ventilators, at providing adequate ventilation and acceptable IAQ. In particular, their impact on the ventilation capacity, the concentrations of
indoor chemical and microbiological contaminants, and the potential improvement in the respiratory health of children enrolled in the study was to be assessed. This presentation will focus on the preliminary ventilation and IAQ results obtained during this study.

2. Experimental Methods

2.1 Recruitment, Study Design, and Intervention

This study enrolled homes with children under the age 10 in both an intervention group (55 homes) and control group (24 homes) over the winter and spring of 2017-18 in Kuujjuaq (Nunavik), Canada. The homes in the intervention group had I) forced air furnace with no additional mechanical ventilation system, II) a heat recovery ventilator (HRV) without pre-heating, or III) an energy recovery ventilator (ERV) with a hydronic pre-heating system. It should be noted that the ERV’s allow for some moisture management as they transfer moisture across their heat-transfer core while HRV’s do not. The intervention consisted of a targeted preventative maintenance of the forced-air furnace, ERV, or HRV. Following an initial assessment of the system’s performance an intervention team, consisting of one of the study’s field technicians and one of Kativik Municipal Housing Bureau’s (KMHB) maintenance personnel, conducted an optimization of the existing HRV, ERV, forced-air furnace, and/or local exhaust ventilation system (bathroom/exhaust fan, range hood, etc.). For the furnaces, this involved adjusting the burner temperature, adding a MERV (Minimum Efficiency Reporting Value) 8 filter which captures >90% of the 3.0-10.0 μm aerosol size-fraction [11], and washing the intake grills. For the ERV’s and HRV’s the intervention included balancing the system, washing/cleaning the heat-transfer core, ensuring that the balancing dampers are fully open, and replacing the enthalpic core of one ERV model. In all cases, an optimization or replacement of the localized exhaust system (kitchen, bathroom) was also conducted and the activated charcoal filter in the extractor fans were replaced provided they were not connected to the outdoors. Finally, a detailed home inspection was conducted to identify and correct any environmental issues that might contribute to poor ventilation and IAQ. The occupants were provided with an honorarium of $250 for being part of the intervention group and $50 for being part of the control group. IAQ and ventilation characteristics were measured through field sampling while indoor environmental characteristics were assessed through a home inspection performed by the field technicians. Questionnaires were used to assess occupant characteristics relating to children, lifestyle, perception, and behaviours. No field sampling was conducted with the control group. The institutional research ethics review was conducted by NRC’s Research Ethics Board. Preliminary results for the microbiological measurements have been presented by Degois et al. [12] while the health outcomes from this study will be reported in subsequent publications.

2.2 Indoor Air Quality Measurements

The volatile organic compounds were sampled on Perkin Elmer stainless steel Analytical Thermal Desorption (ATD) passive samplers containing a Tenax TA 60/80 sorbent. Duplicate passive samplers were left in the home (typically in the living room) for a period of 7 days along with one field blank. The samples were then shipped to NRC’s Construction Research Centre where the VOCs were analysed by desorbing them from the tubes with a flow of helium using a Markes Unity thermal desorption system. The thermal desorber temperature ramp was 60 °C min⁻¹ until 300 °C followed by a 5 min hold time. The compounds were then separated and detected on an Agilent 6890A GC and 5973 MSD operating in scan mode from m/z 35 to 300. The GC was equipped with a 30 m x 250 μm i.d. Supelco SPB-624 column and the temperature program was 35 °C for 5 min followed by a 6 °C min⁻¹ temperature ramp to 230 °C. Formaldehyde was measured in the child’s bedroom over a 7-day period using duplicate Waters Sep-Pak® ExPosure cartridges as a passive sampler. The cartridges were subsequently analysed for formaldehyde using high performance liquid chromatography (HPLC) according the ASTM test method D 5197-03 [13]. Settled house dust samples were collected from different surfaces (floor, furniture, shelf etc.) using a QuickTake 30 (SKC Inc.) sampler with a sampling volume of 15 L/min. The dust samples were collected onto a 37 mm cassette with a glass fibre filter. These dust samples were to be analysed for their semi-volatile organic compound (SVOC), endotoxin, house dust mite, and total bacteria content. Ambient air was sampled for its bioaerosol
content using a SASS 3100 Smart air sampler with a flow of 300 L/min for a total volume of 20 m³. The results for the microbiological measurements will be presented in subsequent publications.

The relative humidity (RH) and temperature were measured with an Onset HOBO U12-013 data logger and the CO₂ concentration was measured with a Vaisala GMW21 CO₂ sensor. Carbon monoxide (CO) concentrations were measured using Langan T15n CO sensor. Particulate matter (PM_{2.5}) was measured using a TSI Dustrak 8520 particle counter. All instruments were set to have a 1-min sample integration time for a 7-day measurement period.

2.3 Ventilation Measurements

The average air exchange rate (AER) was measured in the intervention cohort in two locations (living room and hallway) over a weeklong period using the perfluorocarbon tracer (PFT) technique developed by the Tracer Technology Group at Brookhaven National Laboratory [14]. Building air tightness was measured using a Minneapolis Blower Door™ from The Energy Conservatory equipped with a DG-700 pressure and flow gauge and the data was analysed with the TECTITE Airtightness Test Analysis Software. The blower door test was conducted according to the ASTM E 779-03 test method [15]. The airtightness measurements could only be performed in a subset of homes due to the excessive wind conditions encountered in wintertime in Kuujjuaq, which interfered with the conduct of the test. Four homes from the intervention cohort were selected for long-term monitoring of the performance of their ERV (1 x Renewair EV 130, 1 x Venmar K7) or HRV (2 x Venmar Model solo 2.0 ES). In these four cases, the temperature, RH, air flow were measured at the inlet and outlet of supply (intake) and exhaust (return) airstreams within the HRV/ERV units, differential pressure was measured across the units for both supply and exhaust airstreams as well as the ERV’s or HRV’s energy consumption. The long-term monitoring occurred over a full heating season period that covered the entire period of the field campaign.

3. Results and Analysis

Some common observations from the intervention included the presence of partially or fully obstructed dampers in the HRV and/or ERV’s, some ERV pre-heating modules were under or overheating the incoming air stream causing thermal comfort issues, and most furnace, ERV, and HRV filters were heavily fouled. Once these issues were addressed we observed a significant improvement in the IAQ and ventilation rates in the intervention cohort. Table 1 provides and overview of the changes in some health relevant IAQ and ventilation parameters. The data in Table 1 is segregated by the three different intervention cohorts: homes with a forced air furnace and no mechanical ventilation system (No MVS), homes with a heat recovery ventilator (HRV) without pre-heating, and homes with an energy recovery ventilator (ERV) with a hydronic pre-heating system. The statistical significance of any pre- and post-intervention change was determined from the Wilcoxon signed-rank test with statistically significant changes identified in bold.

Following the intervention there was no statistically significant change in the air exchange rate (AER) for the No MVS cohort while the HRV and ERV cohorts experienced a statistically significant increase in AER of +231% and +38% respectively. The much larger increase in AER seen in the HRV cohort is likely due to it having a much lower pre-intervention median AER relative to the ERV cohort (0.13 h⁻¹ c.f. 0.24 h⁻¹). The fact that there was no change no in AER in the No MVS cohort is not surprising as they are not equipped with an ERV or HRV. These homes must rely on infiltration, natural ventilation from open doors and windows (which is unlikely to be commonplace in artic homes during winter), and local exhaust ventilation. Overall, the pre-intervention No MVS and HRV cohorts were significantly under-ventilated considering that in Canada and the Unites States the recommended nominal value is 0.35 h⁻¹ [16, 17]. The airtightness parameters measured with the blower door are excluded in the table as they were only conducted in a subset of homes (n=16) however the median values were found to be 704 CFM for the airflow at 50 Pa (Q_{50}) and 5.66 h⁻¹ for the airtightness at 50 Pa (ACH₅₀). There is no Canadian standard on airtightness for homes however these artic homes are slightly less airtight than those located in more southern regions of Canada. The Natural Resources Canada ecoENERGY retrofit program tested thousands of houses in Ottawa and found that for the homes built between 1940 and 2010 that the mean ACH₅₀ was 5.1 h⁻¹ [18].
The intervention had a significant impact on the concentration in a number of health relevant IAQ parameters. The post-intervention change in RH varied from a reduction of -1.6% to -8.9% however this change was only statistically significant in the No MVS cohort (-1.6%). Although visible mould is commonly observed in homes located in northern and artic communities it was not commonplace in the homes participating in the intervention cohort of this study. Large reductions in the concentration of CO were observed ranging from -5.9% to -46.8% but the changes were only statistically significant in the No MVS and ERV cohort. The observed reductions in PM$_{2.5}$ ranged from -11.6% to -36.0% but were not statistically significant for any cohort. This is not surprising, as increased ventilation should not necessarily lead to a reduction in indoor PM$_{2.5}$ as this would depend on the nature of the source either being indoors (occupant generated PM$_{2.5}$) or from the infiltration of ambient PM$_{2.5}$ into the home. A similar study done in Quebec City, Canada observed no statistically significant change in indoor PM$_{2.5}$ in 43 homes that had the median heating-season ventilation rate increase from 0.17 h$^{-1}$ to 0.34 h$^{-1}$ following the installation of either an HRV or ERV in the home [19]. The remaining parameters in Table 1 are all VOC’s (acetaldehyde, formaldehyde, benzene, and toluene) that all show similar trends in their pre- and post-intervention concentrations. In this case, we observed statistically significant reductions in the concentration of the VOC’s for the ERV and HRV cohorts that ranged from -8.5% to -66.6%. In most cases, the HRV cohort experienced larger reductions in concentration relative to the ERV cohort however this is likely due to the initial AER in the HRV cohort being much lower than in the ERV cohort.

Table 1. Changes in selected median pre- and post-intervention IAQ relevant parameters for the intervention cohort (p-value determined from Wilcoxon signed-rank test and statistically significant changes are identified in bold).

| Parameter (units) | Ventilator (n) | Pre   | Post  | Δ(%)  | p-value |
|-------------------|---------------|-------|-------|-------|---------|
| Relative humidity (%) | No MVS (15) | 32.5  | 30.3  | -6.7  | <0.01   |
|                   | HRV (17)     | 31.2  | 30.7  | -1.6  | NA      |
|                   | ERV (24)     | 30.2  | 27.5  | -8.9  | NA      |
|                   | No MVS (15)  | 3.45  | 1.59  | -1.6  | NA      |
|                   | HRV (17)     | 2.11  | 1.53  | -27.4 | NA      |
|                   | ERV (24)     | 2.99  | 1.59  | -46.8 | <0.01   |
| CO (ppm)          | No MVS (15)  | 1125  | 908   | -19.2 | NA      |
|                   | HRV (17)     | 921   | 630   | -31.6 | NA      |
|                   | ERV (24)     | 812   | 627   | -22.8 | <0.01   |
|                   | No MVS (15)  | 6.0   | 4.8   | -20.0 | NA      |
|                   | HRV (17)     | 4.3   | 3.8   | -11.6 | NA      |
|                   | ERV (24)     | 9.7   | 6.2   | -36.0 | NA      |
| PM$_{2.5}$ (μg m$^{-3}$) | No MVS (15) | 24.50 | 22.81 | -6.8  | NA      |
|                   | HRV (17)     | 25.27 | 10.30 | -59.2 | <0.01   |
|                   | ERV (24)     | 16.08 | 11.70 | -27.2 | <0.01   |
|                   | No MVS (15)  | 17.53 | 17.41 | -0.7  | NA      |
|                   | HRV (17)     | 16.17 | 9.38  | -42.0 | <0.01   |
|                   | ERV (24)     | 9.64  | 8.82  | -8.5  | <0.01   |
|                   | No MVS (15)  | 0.41  | 0.41  | 0     | NA      |
|                   | HRV (17)     | 0.74  | 0.41  | -44.5 | NA      |
|                   | ERV (24)     | 0.73  | 0.41  | -43.8 | <0.05   |
|                   | No MVS (15)  | 4.85  | 5.04  | -3.9  | NA      |
|                   | HRV (17)     | 7.39  | 3.46  | -53.1 | <0.05   |
|                   | ERV (24)     | 10.72 | 3.57  | -66.6 | <0.01   |
|                   | No MVS (15)  | 0.14  | 0.12  | -14.3 | NA      |
|                   | HRV (17)     | 0.13  | 0.30  | +231  | <0.05   |
|                   | ERV (24)     | 0.24  | 0.33  | +38   | <0.05   |
| AER (h$^{-1}$)    | No MVS (15)  | 0.14  | 0.12  | -14.3 | NA      |
|                   | HRV (17)     | 0.13  | 0.30  | +231  | <0.05   |
|                   | ERV (24)     | 0.24  | 0.33  | +38   | <0.05   |
Table 2. Selected Canadian residential indoor air quality guidelines [16].

| Chemical       | Guideline                                                                 |
|----------------|---------------------------------------------------------------------------|
| Acetaldehyde   | Long-term exposure limit (24 hours): 280 μg m\(^{-3}\) (157 ppb)           |
|                | Short-term exposure limit (1 hour): 1420 μg m\(^{-3}\) (795 ppb)           |
| Benzene        | Keep indoor levels of benzene as low as possible                           |
| Carbon Monoxide| Long-term exposure limit (24 hours): 11.5 mg m\(^{-3}\) (10 ppb)           |
|                | Short-term exposure limit (1 hour): 28.6 μg m\(^{-3}\) (25 ppb)           |
| Formaldehyde   | Long-term exposure limit (8 hours): 50 μg m\(^{-3}\) (50 ppb)             |
|                | Short-term exposure limit (1 hour): 123 μg m\(^{-3}\) (100 ppb)           |
| PM\(_{2.5}\)    | Keep indoor levels of PM\(_{2.5}\) as low as possible                    |
| Toluene        | Long-term exposure limit (24 hours): 2.3 mg m\(^{-3}\) (0.6 ppb)          |
|                | Short-term exposure limit (8 hour): 15 mg m\(^{-3}\) (4.0 ppb)            |

4. Conclusions
This intervention field study demonstrated that targeted preventative maintenance and optimization of ventilation systems is effective at improving ventilation rates and IAQ. For the No MVS cohort the majority of the concentration reductions in the reported IAQ parameters was significantly smaller, and often not statistically significant, compared to the ERV and HRV cohorts. This is not surprising, as the changes made during the intervention for the No MVS were not expected to lead to significant increases in the ventilation rates. Overall, large reductions in concentrations of up to -66.6% were observed for the HRV and ERV cohorts when the ventilation rates were increased by +231% and +38% respectively. We show that Canadian homes in the arctic (Nunavik) are significantly under-ventilated when compared to the nominal ventilation rate guideline of 0.35 h\(^{-1}\) for Canada [16] and even more so when compared to the Scandinavian guideline of 0.50 h\(^{-1}\) [20]. However, the concentrations of a number of health relevant IAQ parameters all fell below the Health Canada guidelines shown in Table 2 [21]. We demonstrated that some of the HVAC maintenance issues encountered in northern and remote communities can be readily corrected once they are identified leading to significant improvements in the ventilation rates and IAQ.

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