Performance of a dual core energy recovery ventilation system for use in Arctic housing

Boualem Ouazia*, Ganapathy Gnanamurugan, Chantal Arsenault and Yunyi Li

National Research Council Canada
1200 Montreal Road
Building M-24, Ottawa ON K1A 0R6, Canada

ABSTRACT

The extremes of arctic climate pose severe challenges on housing ventilation systems, energy consumption and demand for space heating for northern remote community residential buildings. As a part of the overall effort to reduce space heating requirements, dwellings are built air tight to reduce heat losses. However, airtight homes require energy efficient and effective ventilation systems to maintain acceptable indoor air quality and comfort, and to protect the building envelope from moisture damage. Heat and energy recovery ventilation systems are used to reduce energy consumption and improve the ventilation rate of housing in Canada's north. Their performance achieved to date has been inadequate due to equipment failures (freezing of cores, partial/full blockage of air flow passages, etc.). This paper presents a rigorous investigation on the performance of a novel dual core energy recovery unit designed for housing in harsh cold climates. The methodology included (1) lab evaluation using climatic chambers to simulate indoor and outdoor conditions identified by certification standard and those identified in the Arctic, (2) side-by-side testing using twin houses to compare whole building performance between a house equipped with a single core ERV and a house equipped with a dual core energy recovery system, then (3) extended monitoring of the dual core technology in Nunavut for proven long-term performance and resilience. This paper discusses the apparent sensible and total efficiencies, flow characteristics, supply air temperature to indoor, frosting occurrence and its impact on the performance of the dual core unit. The dual core technology was found to be more frost-tolerant, capable of withstanding a temperature of down to -40°C without deteriorating its thermal performance, was also found to be able to provide continuous delivery of outdoor air to the space even at very low outdoor temperatures and was able to supply air to the indoor at temperature warmer than 15°C with outdoor temperature of -40°C. The dual core ERV system had higher apparent sensible effectiveness (82% compared to 70% for the single core ERV), a difference of 10 percentage points, and had higher calculated apparent total effectiveness (73% compared to 68%), a difference of 5 percentage points). A house with a dual core ERV showed a significant heating and ventilation energy saving of 6.2% over a week testing period in winter 2017. The technology has been deployed in the Nunavut for extended monitoring since June 2017 for proven performance, resilience and durability in harsh arctic climate.

KEYWORDS

Ventilation, AHU, ERV, Frost, Cold Climate

1 INTRODUCTION

The extremes of the Arctic climate pose severe challenges on housing ventilation and heating systems. Energy consumption and demand for space heating for remote community buildings are very high. In the Arctic/northern regions of Canada the average temperature during winter is -25°C or less, and many northern homes are heated to over 25°C resulting in significant loads on systems (Zaloum, 2010). Typical energy supply (diesel) to Arctic and northern communities is logistically difficult to organize and supply resulting in an electricity price of up to $1/kWh in some Nunavut communities. As a part of the overall effort to reduce space heating requirements, residential buildings are built air tight to reduce infiltration or exfiltration heat losses. However, airtight buildings require energy efficient and effective ventilation systems to maintain acceptable indoor air quality and comfort and to protect the building envelope from moisture damage. Maintaining healthy IAQ in cold climate can be challenging due to the need for sufficient fresh air intake. Without fresh air, carbon dioxide, odors, dust, airborne pollutants and excess humidity are kept indoors, potentially causing or aggravating problems to occupants' health and comfort, and encouraging mold growth. Clearly, effective ventilation is a vital system in a healthy home. A balanced mechanical ventilation system with heat or energy recovery is an ideal way to meet both building codes (NBC, 2015) and the ventilation requirements of standards such as ASHRAE 62.2 (ASHRAE 62.2, 2016) and energy efficiency programs such as R2000 (NRCan, 2014) and many more. The minimum outdoor air flow rates are established by building codes and ventilation standards. Heat recovery ventilation (HRV) and energy recovery ventilation (ERV) are a well-known and effective method to improve energy and ventilation efficiency of residential heating, ventilating and air conditioning (HVAC) systems when designing energy efficient buildings, because they allow adequate outdoor ventilation air without excessive energy consumption. However, ventilation of houses can be problematic in the North where frosting is a significant challenge for the heat/energy exchangers. Frost formation in the exchangers is common in cold regions where the outdoor temperature is below -10°C for the majority of the heating season. The design winter temperatures in the far North are much colder than the very low outdoor test temperature of -25°C that is typically used by HRV/ERV manufacturers when they choose to certify their products at outdoor temperature below freezing. The certification of HRVs and ERVs at very low temperature is an optional test for HVI certification (left to manufacturer to choose conducting this test at any outdoor temperature below freezing). Their performance achieved to date has been inadequate due to equipment failures and conventional problems created by the formation of frost in heat exchangers are partial or full blockage of air flow passages, increase in pressure drop through the heat exchanger or decrease in air flow rate, increase in electric power for the fans, decrease in heat transfer rate between the two airstreams and cold draughts in the space due to low supply air temperatures (Rafati, 2014). As there are no basements in the majority of Arctic homes, an HRV or an ERV must be installed closer to the living areas, which makes quiet operation especially important. Conventional single core HRV/ERV units are usually equipped with frost protection system such as pre-heating of outdoor air or recirculating return air across the heat exchanger and back into the supply air to the house. These defrost strategies can undermine ventilation standards (ventilation rate requirement not met) and the energy saving of the HRV or ERV unit. The aim of this project is to study an innovative dual core design heat/energy recovery system and its applicability for housing in the Arctic. One alternative technology to conventional single core HRV/ERV is a dual core ERV unit designed for continuous ventilation with two parallel heat exchangers and patented damper that address the frost protection concerns by periodically direct warm air (return air from indoor) through one of the two cores while outdoor air gains heat from the other.

2 METHOD

The experimental work consisted of a rigorous investigation on the performance of an innovative dual core energy recovery unit designed for housing in the Arctic. The methodology began with a laboratory evaluation using two climatic chambers to simulate indoor and outdoor conditions identified by certification standard CSA-C439 (CAN/CSA-C439, 2015) and those identified in the Arctic, followed by a side-by-side testing using twin research houses to compare whole building performance between a reference house equipped with a single core ERV and a test house equipped with a dual core energy recovery unit, then deployment of the dual core technology in the Arctic for extended monitoring for proven long-term performance and resilience.

2.1 Description of the Technology

A dual core air handling unit comes with a regenerative cyclic dual core heat exchanger, based on the cyclic storage and release of heat in the corrugated plates alternately exposed to exhaust and intake air. It includes a supply and an exhaust fan and two plate heat exchangers which act as heat accumulators. In between the cores is a patented damper section which changes over every 60 seconds to periodically direct warm air through one of the two cores while outside air gains heat from the heated plates in the other core. Before each fan is a filter section to filter the air. The schematic of the unit with the two sequences is presented in Figure 1, with a description of the 2 sequences below. During *Sequence 1,* exhaust air charges Core B with heat from exhaust warm air from indoor and Core A discharges heat to supply air, and during *Sequence 2* the exhaust air charges Core A with heat from exhaust warm air from indoor and Core B discharges heat to supply air. The damper is controlled by 2 internal thermostats (thermostat 1 in the supply air set to 15°C and thermostat 2 in the exhaust air set to 20°C) to ensure that comfortable air delivery temperatures are achieved in all conditions. When the exhaust air temperature is lower than 20°C, the unit runs in energy recovery mode (cycling every 60 seconds). When the exhaust air temperature is higher than 20°C and supply air temperature higher than 15°C, the unit runs in free cooling mode (cycling every 3 hours). Finally, when the exhaust air temperature is higher than 20°C and supply air temperature lower than 15°C, the unit runs in energy recovery mode until the supply air temperature becomes higher than 15°C then it will revert to free cooling mode.

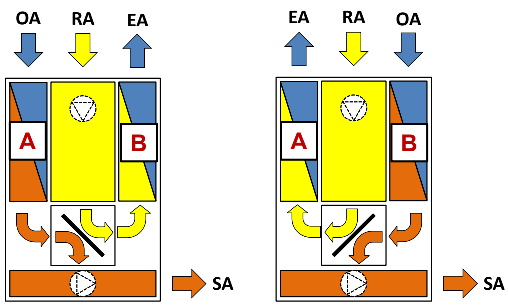


Figure 1 – Principle of function – sequence 1 (left) and sequence 2 (right)

2.2 Laboratory Testing

The experimental facility used for the laboratory testing to perform a first round of short-term cold climate performance tests, was a combination of a dual climatic chambers and an HRV/ERV test rig installed between the indoor and outdoor climatic chambers as shown in Figure 2. The outdoor climatic conditions can be varied over a range of - 40 to + 40 ± 1.0°C with the capability of maintaining a steady state set point. Simulated indoor climatic conditions can be varied from 20°C to 30 ± 1.0°C with the capability of maintaining a steady state ambient humidity (30 to 60 % RH).

Figure 2 – Laboratory experimental setup showing climatic chambers and dual core unit

Air was drawn from two environmental chambers at desired conditions set in the chambers. In order to determine the efficiency and when frosting occurs in the dual core unit, several properties are measured at different locations in the test facility. Two airflows were measured using Nailor type airflow elements. Airflow elements were installed in the supply and exhaust ducts to measure the mass flow rates of dry air. Pressure taps were placed at the inlet and outlet of unit (supply and exhaust airstreams) to measure the static pressures, connected by PVC tubes to the pressure transducers integrated in a designed pressure transducer box. The temperature and relative humidity of the air were measured using RH&T probes, which were calibrated over a temperature range of -20°C to +40°C and over an RH range of 10% to 90%. The temperature and RH were measured in the supply and exhaust airstreams at the inlets and outlets of the unit, exactly where the static pressures were measured.

A series of experiments were conducted to gather data on the thermal and ventilation behaviour, and performance of an ERV unit with dual heat exchangers when subjected to steady state climatic indoor and outdoor conditions. Results obtained from experiments were used to evaluate the apparent sensible and total efficiencies, impact of potential build-up of frost on the thermal and ventilation performance of the dual core technology. The conditions in the indoor chamber were set at indoor condition identified by certification standard CSA-C439 and at realistic indoor condition identified in northern homes. The conditions in the outdoor chamber were varied in a range of temperatures below 0°C to challenge the unit under test with extreme cold outdoor temperatures. The experimental evaluation of the performance of a dual core unit was done with supply and exhaust airflows calculated for the CCHT houses. The total ventilation requirement (ASHRAE 62.2, 2013) takes into account people air needs and house air needs and is calculated using the following equation;

$$Q_{tot} = 0.03A_{floor} + 7.5(N_{br} + 1) \qquad (1)$$

Where Q_{tot} is the required ventilation rate, A_{floor} is the house floor area and N_{br} is the number of bedrooms in the house. The CCHT twin houses have a floor area of 210 m^2 (2260 ft^2) with 4 bedrooms, which require a total ventilation rate of 47.2 L/s (105 cfm). The dual core unit was then tested at balanced supply and exhaust airflows set at 47.2 L/s, following the experimental design presented in Table 1.

Table 1 – Experimental design

Tests	Mode	Indoor Conditions	Outdoor T [°C]
1 - 5	Heating mode with standard conditions Identified by CSA-C439/HVI	22°C & 40%	0, -10, -20, -30, -35
6 - 10	Heating mode with identified northern indoor conditions	25°C & 55%	0, -10, -20, -30, -35

After each run the outdoor chamber was reset at a temperature higher than zero to allow the meltdown of any potential frost build up in the two heat exchangers before the next run. This allowed the same initial condition at the start of each test; i.e., consistently no presence of frost in heat exchangers at the start of each test permits comparison between test results.

2.3 Side-by-side Testing

The Canadian Centre for Housing Technology's (CCHT) twin research houses shown in Figure 3 were used for the comparative side-by-side testing (Ouazia, 20016) between a dual core ERV (installed in the Test House) and conventional single core ERV (installed in the Reference House). These houses are typical 2-storey wood-frame houses, with 210 m^2 liveable area, designed and built to the R-2000 standard. The twin-house research facility features a "simulated occupancy system". Each house features a standard set of major appliances typically found in North American homes. The simulated occupancy system, based on home automation technology, simulates human activity by operating major appliances (stove, dishwashers, washer and dryer), lights, water valves, fans, and other sources simulating typical heat gains. The schedule is typical of activities that would take place in a home with a family of two adults and two children. Electrical consumption is typical for a family of four and hot water draws are set in accordance with ASHRAE standards for sizing hot water heaters. The heat given off by humans is simulated by two 60 W (2 adults) and two 40 W (2 children) incandescent bulbs at various locations in the house. The CCHT research houses are equipped with a data acquisition system (DAS) consisting of over 250 sensors and 23 meters (gas, water and electrical). A computer in the garage reads the sensors every 5 minutes and provides hourly averages. Meter data and a few other measurements are recorded on a 5 minute-basis. The DAS captures a clear history of the house performance in terms of temperature, humidity and energy consumption. A complete set of weather data is available from a nearby CCHT-operated weather station, including temperature, humidity, wind speed and direction, solar radiation and precipitation.

Figure 3 - CCHT twin houses

The side-by-side testing involved first benchmarking the houses for a set 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 programing the dual core unit to match the single core ERV supply and exhaust airflows in the *Reference House*, and finally monitoring the performance of the two houses side-by-side for one week during heating season 2017.

2.4 Field Monitoring

The dual core unit has been deployed in the mechanical room of a triplex on the Canadian High Arctic Research Station (CHARS) in Cambridge Bay (Nunavut) as shown in Figure 4. The instrumentation of the unit and the deployment of dedicated data logging system were implemented in March 2017 and the long-term monitoring started in June 2017, and continues for at least one full year with already captured full winter season 2017/2018.

Figure 4 – Triplex on CHARS Campus and deployed dual core unit

2.5 Performance Evaluation

The performance of the innovative dual core ERV unit is primarily determined by its apparent sensible effectiveness ASE and apparent total effectiveness (ATE) as described in ASHRAE testing standard (ASHRAE 84, 2013) and Canadian testing standard (CAN/CSA-C439, 2015), its pressure drop, flow characteristics, supply air temperature, frosting occurrence and whole house energy consumption. The measured temperatures and relative humidities across the tested unit were used to calculate the ASEs and ATEs. The supply and exhaust flows were assumed equal (based on balancing flows at the beginning of the test). The ASE and ATE were calculated using Equation 2.

$$\varepsilon = \frac{m_s(X_{SI} - X_{SO})}{m_{min}(X_{SI} - X_{EI})} \qquad (2)$$

where, ε is the sensible, latent, or total heat effectiveness. X is the dry-bulb temperature, T, humidity ratio, w, or total enthalpy, h, respectively, at the supply inlet and outlet and at the exhaust inlet of the unit. m_s *is the* mass flow rate of the supply, m_e *is the* mass flow rate of the exhaust and m_{min} *is the* minimum value of either m_s or m_e.

3 RESULTS AND DICUSSION

3.1 Airflow

The measured supply and exhaust airflows from the lab testing undertaken with identified indoor conditions by certification standards CSA-C439 and the Home Ventilating Institute (HVI, 2016) showed, no sign of flow restriction due to frost occurrence as shown in Figure 5. The results from tests undertaken with identified northern indoor conditions (warmer and more humid indoor conditions) showed a low decrease in the supply and exhaust airflows starting at outdoor temperatures below -20°C, as shown in Figure 6. The decrease became more pronounced during the longest test done at an outdoor temperature of -35°C suggesting that the decrease would continue for longer testing period under extreme cold outdoor conditions. The risk to choke the flows completely in extreme harsh outdoor conditions will be or not confirmed through ongoing extended monitoring of the same unit in Nunavut.

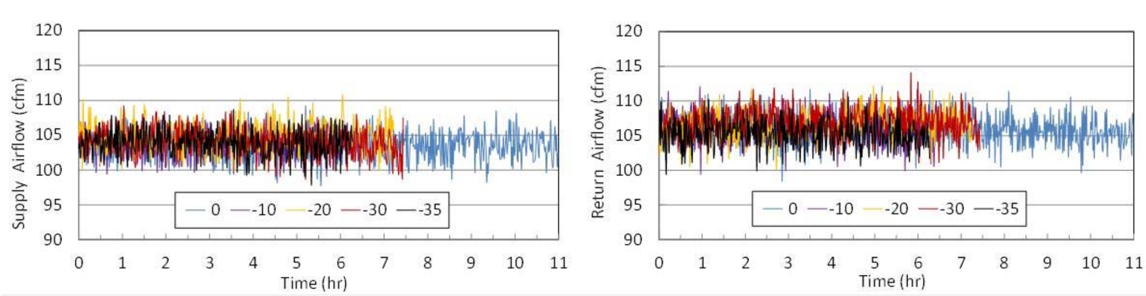


Figure 5 – Measured supply (left) and Exhaust (right) airflows with CSA-C439 indoor conditions

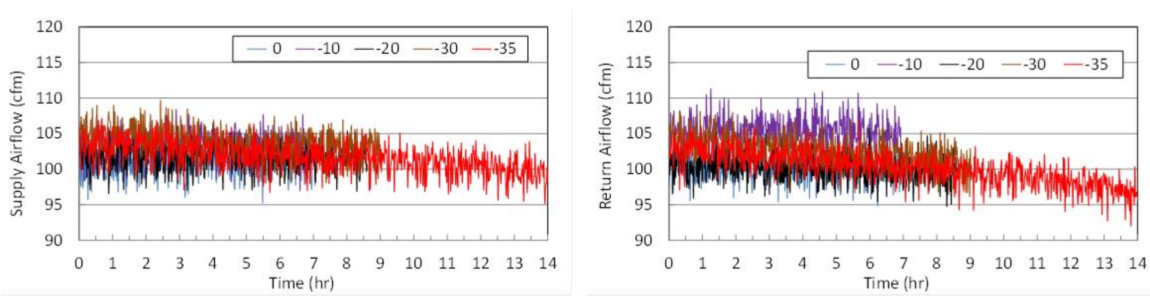


Figure 6 - Measured supply (left) and Exhaust (right) airflows with Northern indoor conditions

The side-by-side testing using the twin houses has clearly shown that the dual core ERV (as shown on the right plot of Figure 7) showed no sign of frost problems and continued to provide outdoor air throughout Ottawa’s cold testing days without stopping to defrost, unlike the single core ERV which had to spent hours defrosting as shown in the plot on the left side of Figure 7.

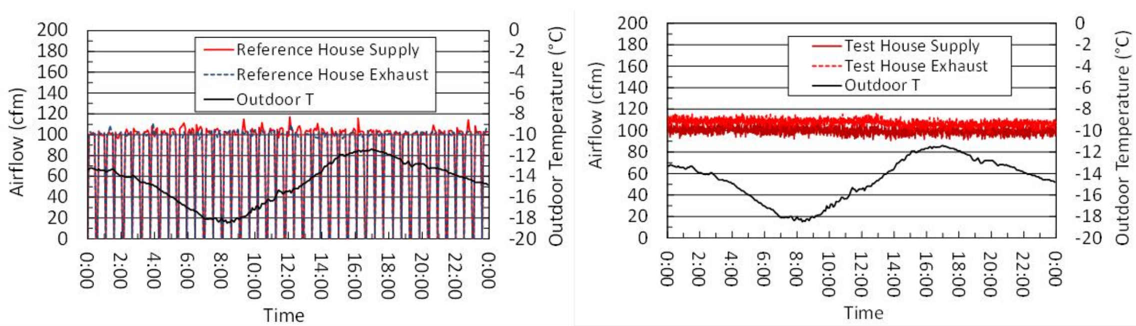


Figure 7 – Measured airflows from side-by-side testing, Reference House (left) and Test House (right)

The frequent defrost cycles of the single core ERV led to reduced amount of outdoor air delivered to the reference house, leading to the situation where the reference house would be under ventilated than the test house, and not meeting the ventilation requirement. This is a common situation for single core HRV/ERV units installed in extreme cold climates.

3.2 Effectiveness

The effectiveness of the dual core ERV unit (with two heat exchangers) in transferring sensible and total energy from exhaust airstream to supply airstream over a wide range of outdoor operating temperatures are presented for indoor conditions identified by CSA-C439 in Figure 8 and for Northern indoor conditions in Figure 9. The calculated ASEs from testing periods with indoor operating conditions identified by CSA-C439 ranged from 82.2% to 93.6% (averaged to 86%), and they were much higher than the claimed ASEs for conventional single core HRVs/ERVs.

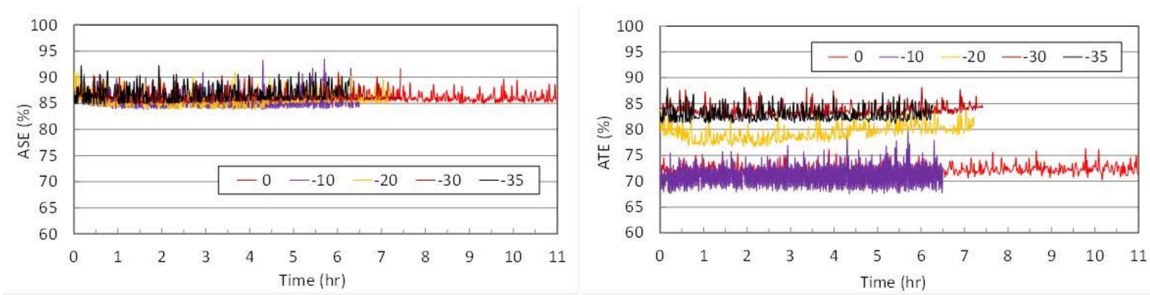


Figure 8 - Calculated ASE (left) and ATE with CSA-C439 indoor conditions

The calculated ATEs for the same indoor operating conditions identified by CSA-C439 ranged from 59.4% to 88.1%. The values increased with decreasing outdoor temperature, and were closer to the calculated values of ASEs at outdoor temperatures lower than -20°C. The increase of the ATE with the decrease of outdoor temperature is due to the condensation formed on the exhausting heat exchanger (warm exhaust air melting the frost). When the cycle changes, the outdoor air is passed over the heat exchanger and that moisture is added back to the airstream.

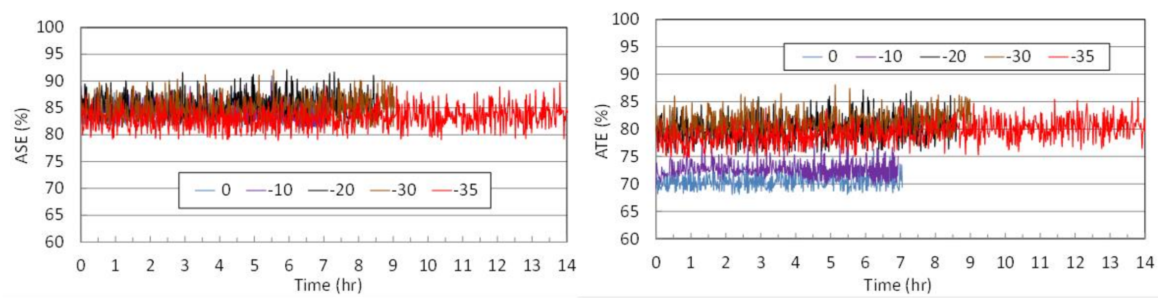


Figure 9 – Calculated ASE (left) and ATE with Northern indoor conditions

For both indoor operating conditions identified by CSA-C439 and Northern indoor conditions, the results showed that the ASE is stable (no reduction) with outdoor temperature variations. However, the results showed improvement of the ATE with decreased supply outdoor temperature. This could be explained by the fact the ATE depends on the latent heat (moisture in the air) and with the dual core design, condensation forms on the exhausting heat exchanger (melting the frost build-up by the exhaust warm humid air). When the cycle changes, the outdoor air is passed over the heat exchanger and that moisture is added back to the airstream. The ASE and ATE of a single core ERV and dual core ERV obtained from the side-by-side testing in the CCHT are plotted in Figure 10. The calculated ASE of the dual core ERV had an average value of 81.5% and ranged from 76.2% and 96.9%. The single core ERV in the reference house had an average ASE of 69.5 during the same testing period and ranged from 65.9% and 78.3%, a difference of at least 10 percentage points. The ATE which takes into account the latent heat of the single core ERV varied between 60.5% and 77.7%, with an average value of 68.1%. The dual core ERV unit had an ATE between 57.7% and 92.3%, with an average value of 72.7% slightly higher than the single core ERV. Overall results showed clearly that the dual core ERV unit over performed the single core ERV in terms of apparent sensible and total efficiencies.

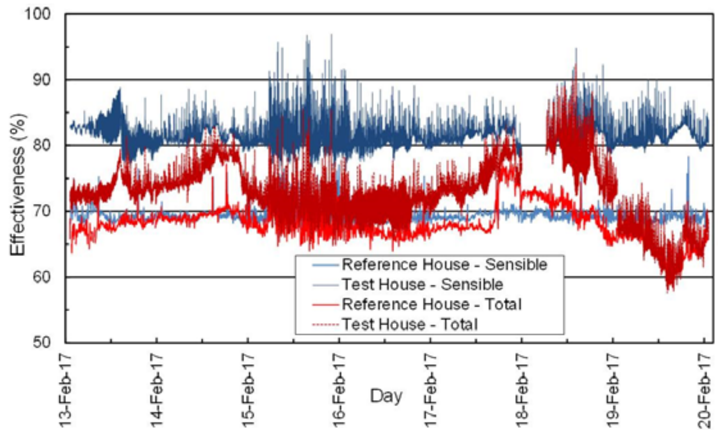
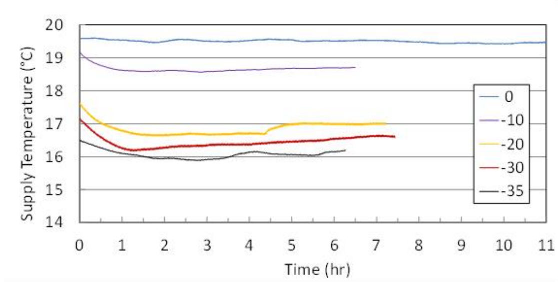


Figure 10 – ASE and ATE from side-by-side testing using the CCHT twin houses

3.3 Supply Air Temperature

Ventilation air must be introduced into the occupied zone in a way that avoids causing discomfort to the occupants, at acceptable minimum temperatures, 17°C for floor distribution and 13°C for ceiling distribution, as specified by the National Building Code of Canada (NBCC, 2015) and National Standard of Canada CSA F326 (CAN/CSA F-326, 2013).

The measured supply air temperatures for indoor operating conditions identified by CSA-C439 to the indoor are presented in the plot on the left of Figure 11 and the values ranged from 15.9°C to 20.6°C. The measured supply air temperature for Northern operating indoor conditions to the indoor are presented in the plot on the right side of Figure 11 and the values ranged from 15.3°C to 22.8°C. As expected again, the values decreased with decreasing supply outdoor temperature, providing a supply air temperature as low as 15.3°C which fairly low and will require either a provision for tempering by blending the supply air with room air or preheating before direct delivery to the occupied spaces.



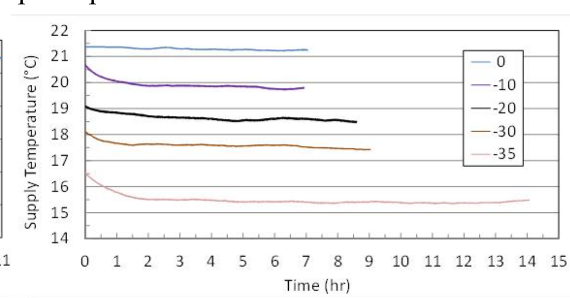


Figure 11 – Measured supply air temperature with CSA-C439 (left) and Northern (right) indoor conditions

The temperature and relative humidity of the supply air from outdoor to the single and dual core units measured during the side-by-side testing are presented in Figure 12. The difference in conditions between the inlet to a single ERV and the inlet to the dual core unit was because the single core ERV had same duct used for supplying air from outdoor, and the dual core unit alternate the exhaust and supply from/to outdoor. The supply and exhaust duct were for one receiving cold air from outdoor and during next minute receiving warm air from indoor. The supply outlet air temperature from the single core ERV in reference house varied between

11.5°C and 17.9°C and daily average values ranged from 13.4°C to 16.6°C. The average value over testing period was 14.6°C, below the acceptable minimum temperature of air that would be introduced to occupied zone which means tempering of the supplied air would be required. The supply outlet air temperature from the dual core ERV in test house varied between 17.5°C and 20.3°C and daily average values ranged from 18.7°C and 19.6°C. The average value over the testing period was 19.2°C, higher than the acceptable minimum temperature of air that would be introduced to occupied zone which means no or less tempering of the supplied air would be required. The temperature of the supplied air to the house was higher (3 to 6°C) from the dual core unit than the single unit. This was due to the much higher ASE of the dual core unit (higher than 80%) from regenerative cyclic dual cores. The supply air to the test house would require less tempering by the furnace to meet the thermostat set point of 22°C, which means that a dual core unit provided more pre-heating than a single core ERV and would lead to additional energy saving.

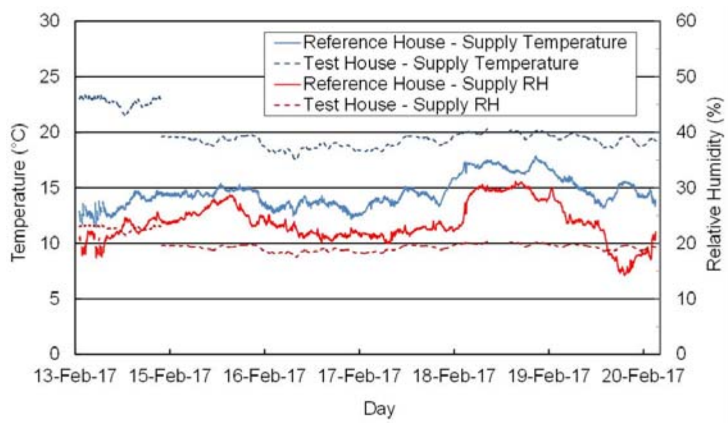


Figure 12 – Measured supply air temperature from side-by-side testing

3.1 Energy

Changes in house performance due to the innovation were addressed through comparison of the test house performance (with dual core ERV) to the reference house performance (with single core ERV). The recorded reference house and test house energy consumptions included; heating energy consumption (furnace natural gas consumption), furnace fans electrical consumption, single core ERV fans electrical consumption and dual core ERV fans electrical consumption. The daily and total heating and ventilation energy consumption and savings for the dual core ERV are presented in Table 2.

Table 2 – Daily and total space heating and ventilation energy consumption

Day	House 1 (M24-B)				House 2 (M24-C)				House 2 ([1])	Savings [MJ]	Savings [%]
	Furnace Natural Gas [ft^3]	Furnace Fan [kWh]	Exhaust ERV Fan(s) [kWh]	Total [MJ]	Furnace Natural Gas [ft^3]	Furnace Fan [kWh]	Exhaust ERV Fan(s) [kWh]	Total [MJ]			
1	383.8	1.789	1.026	415.5	383.3	1.843	0.935	414.8	430.1	15.3	3.5%
2	308.0	1.417	0.984	334.0	301.8	1.484	0.878	327.3	346.7	19.5	5.6%
3	340.8	1.565	0.994	369.2	337.3	1.622	0.896	365.3	382.7	17.4	4.5%
4	277.0	1.333	1.002	301.0	269.8	1.390	0.882	293.1	313.0	19.8	6.3%
5	187.3	0.974	0.984	204.8	180.0	0.991	0.883	196.9	214.6	17.7	8.3%
6	152.3	0.870	0.987	167.5	150.0	0.898	0.900	164.9	176.4	11.5	6.5%
7	203.3	1.020	1.008	222.0	185.5	0.998	0.881	202.7	232.1	29.4	12.7%
Mean	264.6	1.281	0.998	287.7	258.2	1.318	0.894	280.7	299.4	18.7	6.2%

[1] expected House 2 energy consumption in a benchmark configuration [MJ]

The expected test house consumption in benchmark configuration (i.e. operating the benchmark ERV equipment) is first calculated. From this the overall energy savings when the dual core ERV system is operating is calculated. Savings are calculated by subtracting the measured House 2 experiment consumption from the calculated House 2 benchmark consumption. The average energy savings when operating the dual core ERV compared to the benchmark ERV over the period of the study was 6.2%.

4 CONCLUSIONS

In comparison with conventional single core ERV, the dual core energy recovery system designed with two parallel regenerative heat exchangers and controlled cycling damper;

- Had higher ASE and ATE from lab and side-by-side testing than the single core ERV.
- More frost-tolerant, capable of withstanding a temperature of down to -40°C without deteriorating its thermal performance.
- Showed no sign of frost problems at outdoor temperature below -10°C and provided continuous supply of outdoor air without stopping to defrost, unlike the conventional single core ERV which spent hours defrosting over cold days of the side-by-side testing.
- The dual core technology was capable to provide air at the supply outlet at temperature up to 6°C higher than air temperature supplied by a single core ERV and complied more with the acceptable minimum temperature of ventilation air that would be introduced into an occupied zone (17°C for floor distribution).
- Its incorporation in the test house showed a significant saving in heating and ventilation energy consumption, ~6.2% (18.7 MJ/day).
- Extended monitoring of the technology in harsh cold climate is strongly recommended for proven performance and resilient in the North.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

ANSI/ASHRAE 62.2 (2016). *Ventilation for acceptable indoor air quality*. ASHRAE, Atlanta, GA.

ANSI/ASHRAE Standard 84 (2013). *Method of testing Air-to-Air Heat/Energy exchangers*, ASHARE, Atlanta, GA.

Canadian Centre for Housing Technology (CCHT). www.ccht-cctr.gc.ca.

CAN/CSA-C439 (2015). *Standard Laboratory Methods of Test for Rating the Performance of Heat/Energy Recovery Ventilators*. Canadian Standard Association.

CMHC/SCHL (2016). Research Report: *Survey of HRV/ERV Performance Issues in Canada's Near North and Far North*. Final Report.

CAN/CSA-F326-M91 (2013). *Residential Mechanical Ventilation Systems. National Standard of Canada, Canadian Standards Association, Rexdale, Ontario.*

Home Ventilating Institute (HVI). Available online at www.hvicertified.org

Rafati, M.N., Fauchoux, M., Besant, R., Simonson, C. (2014). *A review of frosting in air-to-air energy exchangers*. Renewable and Sustainable Energy Reviews, 30, 538-554.

National Building Code of Canada (NBCC) (2015).

Ouazia B., Swinton, M.C., Julien, M., Manning, M. (2006). *Assessment of the enthalpy performance of houses using energy recovery technology*. ASHRAE Trans. 112(1) 26-33.

R-2000 Homes Standard (2014). Natural Resources Canada.

Zaloum, C. (2010). *Technical advice to task force on Northern mechanical ventilation equipment design and testing*. Ottawa, Canada Mortgage and Housing Corporation.